A MANUAL

OF

PHYSICS

BY

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PART IV

BOOK V—MAGNETISM AND ELECTRICITY

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BOOK V

MAGNETISM AND ELECTRICITY

CHAPTER I

PROPERTIES OF MAGNETS

251. Natural Magnets.—It was known in very early times that certain naturally occurring black stones had the curious property of attracting to themselves small pieces of iron. These stones were found in Magnesia, and were consequently given the name of **magnets**. It was found that these stones (which consist of a black oxide of iron, Fe_3O_4) could communicate this peculiar property, which was called **magnetism**, to pieces of iron or steel, which in their turn thus became magnetised, and were also known as magnets. The magnets used in laboratories consist of pieces of hard steel, usually in the form of rods or bars. They are magnetised, not by contact with a natural magnet, but more conveniently and more powerfully by means of an electric current (§ 325).

It was later found that if a magnet, either artificial or natural, is suspended so as to be free to turn in a horizontal plane it will always set in a definite direction, and will return to that direction if displaced. This property can obviously be used for enabling a ship to steer a proper course, and hence the natural magnets were called "lodestones," that is, "leading stones." The magnetic compass, which consists of a small magnetised needle delicately supported on a fine point, is the modern development of the lodestone.

252. Magnetic Poles.—It is found that for many purposes the magnetic forces exerted by a magnet may be regarded as acting towards or from certain definite points in the magnet. These points are known as the **poles** of the magnet. Every

magnet has at least two such points, but may have more. A bar magnet which has been uniformly magnetised will have two such poles, situated near the ends of the bar. The straight line joining the two poles of the magnet is known as the **magnetic axis** of the magnet, and the length of this line (which is generally about five-sixths of the length of the bar) is known as the **magnetic length** of the magnet.

If the magnet is suspended, say by a piece of unspun silk, so as to be free to turn in a horizontal plane, the magnet will come to rest with its axis pointing in a direction which is approximately north and south. The pole which is situated at the north end of the magnet is known as the **north-seeking** pole, or more usually simply the **north pole** of the magnet, while that at the other end is known as the **south-seeking** pole, or simply as the **south pole** of the magnet. It is usual to mark the north pole, either with the letter N, or often simply with a scratch or a dab of red paint. The poles can at any time be identified by suspending the magnet as described and noting the direction in which it sets. The pole pointing approximately towards the north will be the north pole of the magnet.

The two poles differ in character. Let us take two magnets, and suspending one of them, present the north pole of the other towards the north pole of the suspended magnet. It will be found that the suspended pole moves away from the approaching pole. The two north poles repel each other. Similarly, if the south pole of the other magnet is brought close to the south pole of the suspended magnet, the latter again is repelled.

On the other hand, if the south pole of the one magnet is brought near the north pole of the other, the suspended magnet turns towards the other, showing that the two unlike poles are attracting each other.

Thus like poles repel each other, and unlike poles attract.

We can use this property to identify the poles of an unmarked magnet. The pole of the magnet which repels the north-seeking pole of a compass needle is the north pole of the magnet. In the mathematical treatment of magnetism this difference between the poles of a magnet is represented by calling the north pole "positive" (+), and the south pole "negative" (−). The two poles are thus said to be of **opposite sign.**

253. Magnetic Substances.—Substances which can be acted upon by magnets are known as **magnetic substances.** Iron, steel, and in a lesser degree nickel and cobalt, are the only substances possessing magnetic properties in any appreciable degree. Thus a magnet which will strongly attract a piece of iron or steel will exert no perceptible influence on a match stick or a piece of copper wire. It can be shown by the use of very powerful magnets and sensitive apparatus that all substances are more or less affected by magnetic forces; but, except on the substances named above, the action is so small as to be quite negligible.

If we bring up one end of a bar of iron close to, say, the north pole of a compass needle or suspended magnet, the magnet will turn towards the iron, showing that there exists an attractive force between the pole and the iron. If now we invert the piece of iron so as to present the other end to the same pole, the magnet will again turn towards the iron. Thus the magnetic pole attracts and is in turn attracted by both ends of the unmagnetised piece of iron. If, however, the iron is a magnet, then, as we have already seen, one end of it will attract and the other end will repel the north pole of the magnet. Hence the distinction between a magnet and a piece of magnetic substance which has not been magnetised is this: that any part of the piece of magnetic substance will be attracted by either pole of a permanent magnet, while in the case of a magnet one part will be attracted and another part will be repelled. Thus a body which attracts or is attracted by a magnet may either be another magnet or simply a piece of unmagnetised magnetic substance. *The only sure proof that a given body is a permanent magnet is its power to produce repulsion.*

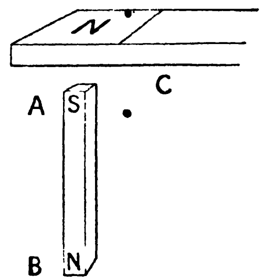


FIG. 204.—Experiment to illustrate Magnetic Induction.

254. Magnetic Induction.—Let us examine the attraction between a magnet and a magnetic substance a little more closely. Place an unmagnetised bar of iron in a vertical position (Fig. 204), and place a small compass needle with its north pole near the end B of the bar. Since the latter

is unmagnetised, the pole will be attracted and will point towards the iron. Now bring up a strong magnet C, with its north pole directly over the end A of the iron bar. The north pole of the compass needle will now be repelled by the end B of the bar, thus proving that the iron bar has become a magnet with its north pole at the end B, and consequently with a south pole at A. The bar AB is said to be *magnetised by induction*.

The north pole of the magnet C is called the inducing pole, while the poles produced in AB are *induced poles*. The inducing pole always induces a pole of the opposite kind on the part of the iron nearest to it, and a pole of the same kind on the part of the iron farthest away from it.

The attraction of a magnetic pole for an unmagnetised piece of iron is due to induction. When a magnet is brought near an unmagnetised substance it induces a pole of opposite kind on the portion of the substance nearest to it, and these two poles, being unlike, attract each other. The inducing pole and the second induced pole, being like poles, repel each other, but as this second pole is much farther away than the first, the force between them is comparatively negligible, for, as we shall see, the force between two poles decreases very rapidly as the distance between them is increased.

If the bar AB is of soft iron, the effects will disappear as soon as the magnet C is removed, leaving the bar again in an unmagnetised condition. If, however, the bar AB is made of steel it will be found to be slightly magnetised after the magnet C is removed, and the effect can be considerably increased by hammering the bar while the magnet is in position. In this way a permanent magnet can be obtained by induction. It must be noticed that the strength of the magnet C is not in any way diminished by the process. It produces a magnetic state in the bar AB without losing any fraction of its own magnetism.

255. Production of Magnets.—In practice magnets are always made by the action of an electric current (§ 325). They can, however, less satisfactorily be made by the action of permanent magnets. There are two methods in common use.

1. Single Touch.—The steel bar to be magnetised is laid flat on the table, and a strong bar magnet NS is held in a vertical position with its north pole touching one end of

the bar (Fig. 205). It is then drawn slowly and uniformly along the bar to the other end; lifted vertically from the bar and carried back at some distance above it into its original position; the operation being repeated some twenty or thirty times. The end B where the pole leaves the bar will be a south pole.

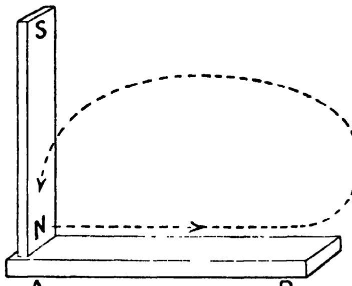


FIG. 205.—Magnetisation by Single Touch.

2. DIVIDED TOUCH.—Two permanent magnets of equal strength are taken and placed on the centre of the bar to be magnetised, with their opposite poles in contact (Fig. 206). They are then drawn slowly apart to opposite ends of the bar, lifted up from the bar, and replaced in their original position. The operation is repeated several times. The end which is touched by the south pole will be found to have north polarity, while the other end will be south.

The simplest magnet we can make has *two* unlike poles, situated at a short distance from each end. Unless the operations of stroking, etc., are very carefully performed, the resulting magnet will often exhibit more than two poles. These can be demonstrated by dipping the magnet into iron filings, when the filings will be found clustering about several different points along the bar. These poles, which are not situated near the end of the bar, are known as **consequent poles.** They are often present in magnets made by the action of other magnets.

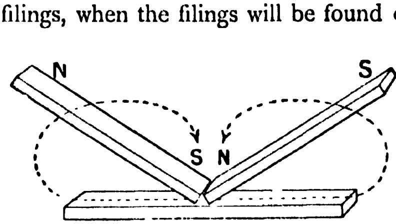


FIG. 206.—Magnetisation by Double Touch.

A bar of steel can, of course, be magnetised purposely to have more than two poles. For example, if we place the north pole of a bar magnet on the centre C of a bar of steel and stroke it from C to A several times, and then repeat the

process with the other half of the bar, stroking with the same pole from C to B, the resulting magnet will have a south pole at each end and a stronger north pole in the middle, as indicated in Fig. 207.

A permanent magnet must be made of steel. Soft iron, though readily magnetised, loses its magnetism with great ease. Steel, though not so readily magnetised as soft iron, retains its properties for a very considerable time. *Even a steel magnet will in time lose its magnetic character*, and the process is greatly accelerated by rough treatment—for example, by dropping it on the floor, hammering it with a hammer, or allowing it to become rusty. The magnetism of any magnet can be completely destroyed by raising it to a red heat (above 800° C.).

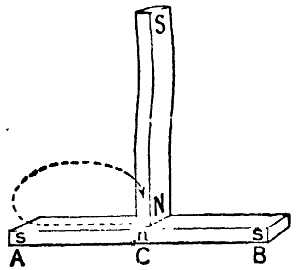


FIG. 207.—Production of a Consequent Pole.

256. **Molecular Theory of Magnetisation.**—Let us take a magnetised piece of watch-spring. It will show only two poles—a north pole at one end and a south pole at the other. Suppose now we break the watch-spring in two. It might be supposed that in this way we should produce one piece of steel possessing only a north pole and another with only a south pole. This is not the case. It will be found that new poles are produced at the fracture, a south pole on the portion carrying the north pole and a north pole on the side nearest the original south pole. In other words, each fragment is a complete magnet, possessing a north and a south pole (Fig. 208). However many times the process is repeated

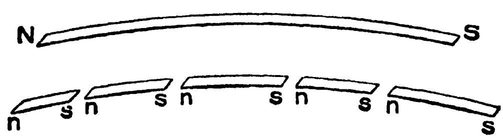


FIG. 208.—Result of dividing a Bar Magnet into Fragments.

the resulting fragments are always complete magnets. *It is impossible by any operation to produce an isolated north or an isolated south pole.*

It was suggested by Ewing that the molecules of magnetic substances are themselves small magnets possessing a north and a south pole. In the case of an unmagnetised piece of iron these molecules are arranged in an entirely haphazard manner. Thus, if a certain number of molecules have their north poles pointing to one end of the rod, there will be on an average an equal number of molecules with their south poles pointing in the same direction. The effect of the south poles will exactly neutralise that of the north poles, and hence the iron as a whole will appear unmagnetised. If, however, we can rearrange the molecules so that the little molecular magnets are all pointing in the same direction, one end of the bar will now be entirely made up of these little north poles and will therefore act as a strong north pole, while the other

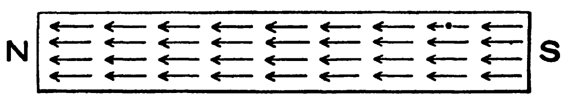


FIG. 209.—Illustrating the Molecular Theory of Magnetism.

end will similarly be a strong south pole (Fig. 209). Since the molecules themselves are indivisible it is evident that into no matter how many fragments we divide the bar one end of each will be made up of north poles, and the other of soutn poles. Hence each magnet must possess at least two poles.

The process of magnetisation, therefore, consists of the rearrangement of the molecules of the magnetic substance. The student can easily apply the theory to the methods of magnetisation already described.

The process can be illustrated on a large scale by taking a test-tube filled with steel filings, and stroking the tube from one end to the other with a strong magnetic pole. It will be found that the tube of filings behaves as a magnet having poles at each end. The steel filings have become small magnets, and have arranged themselves along the tube under the action of the magnetic pole. If now the tube be shaken so as to mix the filings, all traces of magnetisation disappear. The steel filings still retain their magnetisation, but, being now

arranged in a haphazard manner, produce no magnetic effect as a whole. In this condition the tube furnishes us with a picture of a magnetic but unmagnetised substance.

If the new arrangement of molecules after magnetisation is a permanent one, the substance will retain its magnetic properties. If, however, the new arrangement should prove to be unstable, the molecules will return to their original haphazard grouping when the magnetising force is removed,

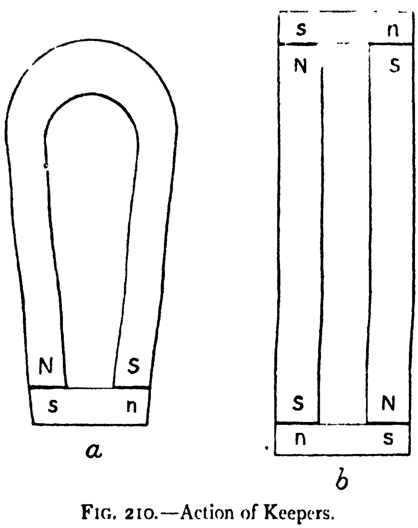


FIG. 210.—Action of Keepers.

and the substance will only be a magnet so long as this force is acting. The former supposition corresponds to the case of steel; the latter to the case of soft iron.

257. Demagnetising Force.—Action of Keepers.—If we consider again Fig. 209 it will be seen that all the north poles of the elementary magnets are pointing in the direction of the north pole of the magnet itself. Now since like poles repel and unlike poles attract, the tendency of the big poles at the ends of the magnet is to cause the elementary magnets to swing round, and thus disturb the arrangement of the molecules which produces the magnetisation. The mere existence of the poles at the ends of the magnet thus produces a force tending to demagnetise the bar. This is known as the

demagnetising force. Thus under the continued action of the demagnetising force even a steel magnet will gradually lose its magnetic properties.

This effect can be very greatly diminished by the use of *keepers*, or armatures as they are sometimes called. Thus in the case of the very common form of magnet, known as the "horseshoe" magnet, shown in Fig. 210*a*, if a small piece of soft iron is placed across the poles of the magnet it becomes magnetised by induction as indicated in the figure. Now the south pole induced in the keeper is very nearly equal to the north pole of the horseshoe magnet, and as it is of opposite sign, and very close to it, the two poles will almost neutralise each other. Similarly, the south pole of the horseshoe magnet is practically neutralised by the north pole induced on the keeper. The system as a whole is therefore practically without any free poles, and the demagnetising force is thus eliminated.

Bar magnets are generally kept in pairs; the north pole of each being placed close to the south pole of the other. Two keepers are required. The arrangement is shown in Fig. 210*b*.

CHAPTER II

MAGNETIC MEASUREMENTS

258. Law of Force between Magnetic Poles.—We have seen that like poles repel and unlike poles attract each other. A few simple observations will be sufficient to show that the force between two poles, whether of attraction or repulsion, decreases very rapidly as the poles are moved farther apart. An ordinary bar magnet, for example, has a practically negligible effect on a compass needle a yard or more away from it. *The force with which two magnetic poles attract or repel each other is inversely proportional to the square of the distance between them.* This law was propounded by Coulomb, and is known as the **Law of Inverse Squares.** It must be understood that although the mechanism by which one magnetic pole exerts a force upon another may be obscure, yet the force exerted is exactly the same in kind as the forces with which we have dealt in Mechanics. It can therefore be measured by any means ordinarily employed for measuring forces if sufficiently sensitive. For example, the magnetic force can be balanced against the pull of a spring balance or against the attraction of gravity on a given weight, and when measured the force between two magnetic poles will be expressed in the usual unit of force—that is, on the C.G.S. system in dynes.

The force also depends on the degree to which the magnets have been magnetised. A knitting needle which has been magnetised by several strokes from a bar magnet will affect a magnetic needle more strongly than one which has only been magnetised by a single stroke. The strength of the magnetic poles therefore differs in different magnets.

A magnetic pole is said to be of unit strength if when placed at unit distance (1 cm.) in air from an equal and similar pole it repels it with a force of 1 dyne.

A magnetic pole is therefore said to have a strength of m

units if, when placed at unit distance from a unit pole, it repels it with a force of m dynes. Thus if we have two magnetic poles of strength m and m' respectively, separated in air by a distance d cms., the force exerted by either of the poles upon the other is given by

$$F = \frac{m \cdot m'}{d^2} \text{ dynes}$$

259. Magnetic Fields.—*Any space in which magnetic force is exerted is called a magnetic field, or field of magnetic force.* Thus all the space around a magnet in which its force of attraction or repulsion can be experienced constitutes the field of the magnet.

The strength of a magnetic field at any point is the force which would be experienced by a unit magnetic pole placed at that point.

The magnetic field at a point is said to be of unit strength if a unit magnetic pole placed at the given point would be acted upon by a force of 1 *dyne.* This unit has been given a special name, and is known as a **gauss.** A magnetic field is, therefore, said to have a strength of H gauss (or H dynes per unit pole) if a unit pole placed in the field experiences a force equal to H dynes. It follows, therefore, that a pole of strength m placed in a field of strength H is acted upon by a force F, given by

$$F = mH \text{ dynes}$$

The strength of a magnetic field is often spoken of simply as "the field."

If the strength and direction of a magnetic field are the same at every point in it, the field is said to be uniform.

260. Magnetic Field due to the Earth.—We have already seen that a magnet suspended so as to be free to turn in a horizontal plane will set in a definite direction, and it can easily be shown that a definite force must be exerted to deflect the magnet from this direction. Thus, although the suspended magnet may be at a great distance from all other magnets, it is obviously in a field of magnetic force. We shall see later that this field is caused by the earth itself, which acts as a large magnet. The strength of the earth's magnetic field varies from place to place on the earth's surface, but it may be regarded as uniform over the area of a laboratory, or even over a large district. The horizontal component of this field, that is to say, the component of it which acts upon a magnet which

is free to turn only in a horizontal plane (like a compass needle, for example), has a strength in this country of about 0·18 gauss. That is to say, a unit magnetic pole would experience a force of 0·18 dyne in a horizontal direction. Magnetic fields are generally measured experimentally by a comparison with the field due to the earth.

261. Equality of the Poles of a Magnet.—The opposite poles of a magnet are always of equal strength. If the magnet has more than two poles, the sum of the pole strengths of all the north poles is always numerically equal to the sum of the strengths of the south poles. This important result can be verified by a simple experiment. A bar magnet is floated on a cork on the surface of a large bowl of wate It is therefore free to move in any direction over the surface. It will of course turn so as to bring its axis into the magnetic meridian, but will show no tendency to move in any direction over the surface of the water. There is rotation, but no translation of the magnet as a whole.

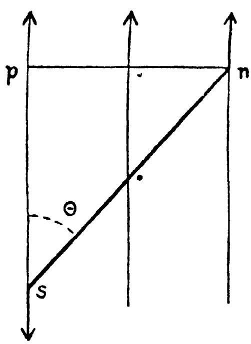


FIG. 211.—Couple on a Magnet in a Uniform Field.

Now if m is the strength of the north pole of the magnet and m' that of the south, and H the strength of the earth's magnetic field, the mechanical force on the north pole is $m \, . \, \mathrm{H}$ towards the north, while that on the south pole is $m' \, . \, \mathrm{H}$ towards the south. Hence the resultant force tending to move the magnet to the north is equal to $m \, . \, \mathrm{H} - m' \, . \, \mathrm{H}$. But, as we have seen, there is no resultant force on the magnet. Hence—

$$m \, . \, \mathrm{H} - m' \, . \, \mathrm{H} = 0$$
$$m = m'$$

The two poles of a magnet are equal in strength, though opposite in character.

262. Couple on a Magnet in a Uniform Field.—As we have just seen, the action of a uniform field on a magnet is one of rotation only—that is to say, it is a pure couple. Let ns (Fig. 211) be a magnet with its magnetic axis inclined at an angle θ to the direction of the uniform field. If m is the pole strength

of the magnet, and H the strength of the field, the mechanical force on each pole is $m \,.\, H$. These forces are parallel, since they both act in the direction of the field, but opposite, since the north pole tends to move in the opposite direction to the south.

The strength of the couple is equal to $m \,.\, H \times$ (the arm of the couple) (§ 52)

$$= m \,.\, H \,.\, np$$

where np is drawn perpendicular to the direction of the field.

$$= m \,.\, H(ns \,.\, \sin \theta)$$
$$= m \,.\, H \,.\, 2l \,.\, \sin \theta$$

where $2l = ns =$ magnetic length of the magnet.

Hence the couple on a magnet in a uniform field of strength H is given by

$$C = 2mlH \sin \theta$$

It is greatest when the magnet is at right angles to the field, and decreases to zero when the magnet is parallel to the field. Thus a magnet, if free to turn, will set itself parallel to the direction of the field.

263. Magnetic Moment of a Magnet.—*The product of the strength of either of the poles into the distance between them is known as the magnetic moment of the magnet.*

Thus M the magnetic moment of a magnet of pole strength m and magnetic length $2l$ is given by

$$M = 2ml$$

If we substitute this value in the equation above, we see that the couple on a magnet of magnetic moment M placed at an angle θ to a uniform field of strength H is given by

$$MH \sin \theta$$

If the magnet is held at right angles to a field of unit strength $H = 1$ and $\sin \theta = 1$, and the couple of the magnet is therefore equal to M. Hence—

The magnetic moment of a magnet is the strength of the couple required to hold it at right angles to a field of unit strength.

264. Lines of Force.—A magnetic field is completely determined if we know at every point in it the strength of the field and the direction in which it acts—that is to say, the magnitude of the force which would be experienced by a unit north pole at any point in it, and the direction in which the pole would

begin to move. The direction of a magnetic field at different points in it can be best represented by a system of *lines of magnetic force.*

A line of magnetic force is a line drawn so that its direction at any point is the direction of the magnetic force at that point.

Thus if ABC (Fig. 212) is a portion of a line of force, the direction of the force experienced by a single pole placed at any point B on the line would be the direction of the curve at B—that is to say, in the direction of the tangent drawn to the curve at B. If it were possible to have an isolated pole, then since the latter would move in the direction of the field it would, if placed at a point A on the curve, describe the curve ABC. Since the force on a north pole is always in the opposite direction to that on a south pole, the two poles would

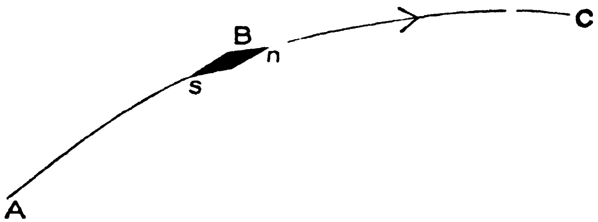


FIG. 212.—Diagram to illustrate a Line of Force.

describe the curve in opposite directions. It is customary to place an arrow on the curve to indicate the direction in which a *north* pole would move.

It is impossible to deal experimentally with isolated poles. Suppose, however, we have a small compass needle at the point B on the line of force. The north pole will be urged along the curve in the direction BC, while the south pole will be urged in the direction BA. The needle if free to turn will therefore set itself along the curve at B, as shown in the figure.

This property can be used to determine the lines of force in a magnetic field. Take a small compass needle anywhere in a magnetic field and allow it to come to rest. It will do so in the direction of the line of force at that point. Make a small dot under the north pole of the compass needle, and move the latter forwards until the south pole of the needle is over the dot. After the needle has again come to rest, make another dot under the new position of the north pole, and

continue the process as far as may be desired. The line joining up this series of dots will obviously be a line of force in the magnetic field. By starting with the compass needle in different positions a series of such lines can be drawn and the whole field mapped out in the plane of the paper. (It must be remembered that though it is usual to consider only the field in one plane, that the magnetic field round a magnet is in three dimensions.)

A magnetic field can also be mapped out roughly by

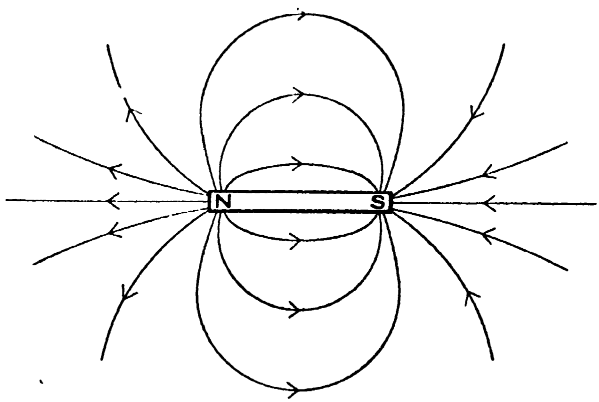


FIG. 213.—Lines of Force due to a Bar Magnet.

sprinkling iron filings over a sheet of paper placed in the field. The filings will become magnetised by induction, and will then set themselves parallel to the lines of the field in exactly the same way as a compass needle. It was the little chains of iron filings obtained in this way that suggested the idea of lines of force to Faraday, to whom it is due.

265. Magnetic Field due to a Bar Magnet.—Since a straight bar magnet is symmetrical about the magnetic axis, the field due to such a magnet must also be symmetrical about the axis. A north pole placed anywhere in the field would be attracted by the south pole of the magnet, and repelled by the north pole. It would, if free to move, be urged from the north to the south pole of the magnet following out a line of force. The lines of force due to a bar magnet therefore run in curves from its north to its south magnetic pole. The field due to such a magnet is shown in Fig. 213.

If, however, we plot the field near a bar magnet in the w described in the previous section we shall not obtain a diagr like Fig. 213, and we shall also find that the diagram which we obtain will depend very much on the position in which we pl the magnet. It must be remembered that the earth posses a magnetic field, and the actual field which we map is **resultant field** obtained by superposing the field due to magnet alone upon that of the earth. At points near *magnet* the former is the more important, and the lines force are similar to those already described, but are sligh distorted by the action of the earth's field. At grea distances from the magnet the earth's field (which is consta while that of the magnet rapidly decreases with the distan

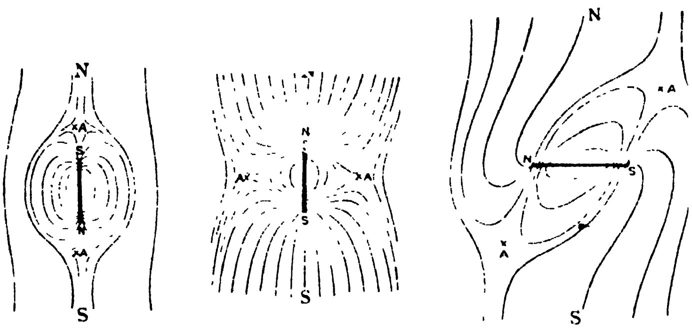


FIG. 214 —Lines of Force near a Bar Magnet placed in the Earth's Fiel

predominates, and the effect of the magnet ceases to l noticeable.

The figures, 214 (*a*), (*b*), and (*c*), show the resultant fiel when a bar magnet is placed (*a*) with its north pole pointir south, (*b*) with its north pole pointing north, and (*c*) with i magnetic axis pointing at right angles to the magnet meridian.

The student is advised to familiarise himself with thes diagrams, and to make clear to himself why the lines of forc run as they do.

266. Determination of the Pole Strength of a Magnet fro the Magnetic Field.—It will be noticed that in each of th diagrams there are certain points (two in each) which seer to be avoided by the lines of force. These are known a

neutral points. *They are places where the magnetic field due to the magnet is exactly equal, and in the opposite direction to that of the earth. The resultant force upon a* pole placed at that point would therefore be zero, and the pole would have no tendency to move in any direction. Similarly, a small compass needle placed at the point would have no resultant couple upon it, and would set *in any* direction.

The simplest case is that of the diagram *in Fig. 214a.* Here the various forces acting on a north pole of *strength* m' at the neutral point are all in the same straight line. They are (*a*) the force Hm' due to the earth which tends to move a north pole placed at A in the direction AN, (*b*) the force $\frac{mm'}{As^2}$ due to the south pole s of the magnet tending to move the pole in the direction As, and (*c*) the force $\frac{mm'}{An^2}$ of the north pole n of the magnet tending to urge the pole in the direction nA. Since the resultant of these three forces at A is zero, the first and third, which act in the same direction, must be equal and opposite to the remaining force. Hence we have

$$Hm' + \frac{mm'}{An^2} = \frac{mm'}{As^2}\ ; \quad m\left(\frac{1}{As^2} - \frac{1}{An^2}\right) = H$$

The various distances can be measured on the diagram obtained by mapping the field of the magnet when placed in this position, and the pole strength m of the magnet can be deduced.

The pole strength of the magnet can also be obtained from the map of the field with the magnet in other positions. In these cases the three forces no longer act in the same straight line. Since, however, the three forces are in equilibrium at the neutral point, the resultant force due to the action of the two magnetic poles must be equal and opposite to the field of the earth. The problem can be solved by substituting the values of the forces, as above, and applying the triangle of forces (§ 27).

267. Calculation of the Field due to a Magnet.—If the pole strength of the magnet is known, the field due to it at any point can be calculated. These calculations are specially useful in the case of two standard positions of the magnet,

known respectively as the "*end on*" and the "*broadside on*" positions.

1. "END ON" POSITION.—A magnet is said to be in the "*end on*" position if the point under consideration lies on the prolongation of the magnetic axis of the magnet.

Thus, let N, S (Fig. 215) represent the poles of a bar magnet, and P a point on NS produced. Let O be the

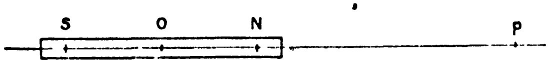


FIG. 215.—Field due to a Magnet—"End on" Position.

centre of the magnet, and let the length of the magnet NS be $2l$, so that $ON=OS=l$. Let d be the distance of the point P from the centre of the magnet O. Then $NP=(d-l)$ and $SP=(d+l)$. Consider a unit north pole placed at P. There will be a force upon it in the direction NP equal to $\frac{m}{NP^2}$ and a force of attraction due to the pole S acting in the direction PS and equal to $\frac{m}{SP^2}$ where m is the pole strength of the magnet. Hence, the resultant magnetic force F experienced by a unit north pole placed at P is given by

$$\begin{aligned}
F&=\frac{m}{NP^2}-\frac{m}{SP^2}\\
&=\frac{m}{(d-l)^2}-\frac{m}{(d+l)^2}\\
&=\frac{m(d^2+2dl+l^2)-m(d^2-2dl+l^2)}{(d^2-l^2)^2}\\
&=\frac{4mdl}{(d^2-l^2)^2}\\
&=\frac{2Md}{(d^2-l^2)^2}
\end{aligned}$$

where M is the magnetic moment of the magnet.

2. "BROADSIDE ON" POSITION.—A line drawn through the centre O of a magnet at right angles to the axis is known as the **magnetic equator.** The magnet is said to be "broadside on" to any point lying on its magnetic equator. For

example, the magnet NS (Fig. 216) is "broadside on" to the point Q.

The forces on a unit pole placed at Q are (*a*) a repulsion in the direction NQ equal to $\frac{m}{NQ^2}$, and an attraction along QS equal to $\frac{m}{SQ^2}$. By the geometry of the figure NQ = SQ, and the two forces are equal in magnitude. Their resultant, therefore, is parallel to NS, that is, in the direction QF, and its magnitude can be found by the parallelogram of forces. It can be shown that if, as before, the length of the magnet $= 2l$, and the distance OQ of the point Q from the centre of the magnet is d, then the field at Q in the "broadside on" position is given by

$$F = \frac{2ml}{(d^2+l^2)^{\frac{3}{2}}} = \frac{M}{(d^2+l^2)^{\frac{3}{2}}}$$

where M is the magnetic moment of the magnet.

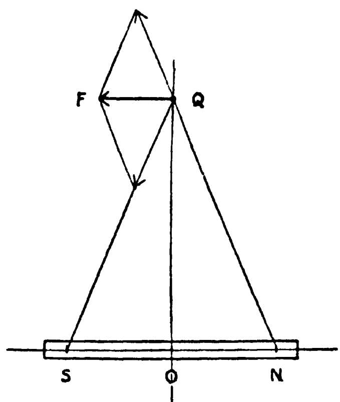


FIG. 216.—Field due to a Magnet—"Broadside on" Position.

268. Approximate Formulæ.—It frequently happens in magnetic experiments that the distance of the point which we are considering from the centre of the magnet is large compared with the length of the magnet itself. Under these circumstances l is small compared with d, and hence l^2 is very small compared with d^2. For instance, if d is $10l$ (the *half* length of the magnet), then l^2 will be only $\frac{1}{100}$th of d^2, and may be neglected in comparison with it without causing an error of more than 1 per cent. The above formulæ can then be considerably simplified. Thus, if the distance of the point from the centre of the magnet is large compared with the length of the magnet, we have for the

"End on" position—

$$F = \frac{2M}{d^3}$$

"*Broadside on*" *position*—

$$F = \frac{M}{d^3}$$

It will be noticed that the field at a given distance from the magnet is exactly twice as great in the "*end on*" as in the "*broadside on*" position.

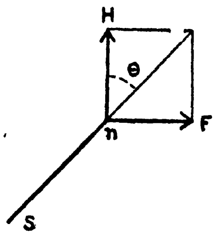


FIG. 217.—Principle of the Magnetometer.

269. The Magnetometer. — A small magnetic needle sets itself, as we have seen, with its axis parallel to the resultant field acting on it. Suppose now that a small compass needle *ns* (Fig. 217) is acted upon by two magnetic fields at right angles to each other and of intensity H and F respectively. Suppose the needle comes to rest making an angle θ with the direction of the field H, then since *ns* produced is the direction of the resultant of H and F we have, by the parallelogram of forces,

$$\frac{F}{H} = \tan \theta$$

$$F = H \tan \theta$$

When the field F is not acting, the needle sets parallel to H. Thus θ is the angle through which the needle is deflected by the introduction of the field F. If this deflexion

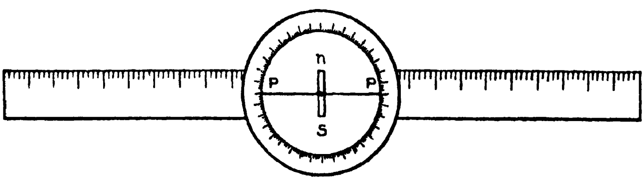


FIG. 218.—The Magnetometer.

can be measured and if H is known, the field F can be determined. The experiment is carried out with an instrument known as the **magnetometer.**

The magnetometer in its simplest form consists of a small magnetic needle *ns* (Fig. 218) carrying a long light aluminium pointer P which moves over a circular scale graduated in degrees. The needle is supported on a steel point at the

centre of the scale so as to turn freely in the horizontal plane. In the absence of other magnets the needle sets in the magnetic meridian under the action of the earth's magnetic field H. The pointer is then at right angles to the meridian —that is, approximately east and west.

The instrument is usually mounted on two wooden arms fitted with boxwood scales, the zeros of which are at the centre of the needle. The reading on the scale thus gives the distance from the centre of the needle. The instrument is generally used with the arms at right angles to the meridian.

270. To determine the Magnetic Moment of a Magnet by the Magnetometer.—The magnetometer is set with its arms at right angles to the needle, that is, parallel to the pointer, and the magnet is placed with its axis along one arm and its centre at some suitable distance d (say 15 cms. or 20 cms.) from the centre of the circular scale. The deflection θ is measured. It is desirable, in order to ensure an accurate result, to reverse the magnet after reading the deflexion so that the north pole occupies the position originally occupied by the south. This eliminates the error which might arise from the poles of the magnet not being at equal distances from its geometrical centre. The new deflexion is measured, and the experiments are then repeated at the same distance from the needle, but on the other arm of the magnetometer. This procedure eliminates the error which might arise if the zero reading of the two scales should happen not to coincide exactly with the centre of the magnetometer needle. The mean of these four deflexions is taken as the true reading.

If F is the field due to the magnet at the centre of the needle, then we have as above

$$F = H \tan \theta$$

But since the magnet is "end on" to the magnetic needle, we have also

$$F = \frac{2M}{d^3}$$

using the approximate formula of § 268. Hence the magnetic moment of the magnet is given by

$$\frac{2M}{d^3} = H \tan \theta$$

$$M = \tfrac{1}{2} d^3 H \tan \theta$$

The readings may be repeated at different distances from the needle. The value of M will be found to be constant within the limits of experimental error. As the formula was deduced on the assumption of the law of inverse squares, the constancy of the value obtained for M affords a proof of the accuracy of the law.

To compare the magnetic moments of two magnets, they may be placed in turn on the magnetometer with their centres at the *same distance* from the needle. If θ, θ' are the deflexions produced, and M, M′ the magnetic moments of the magnets, then, since H and d are the same in both cases, we have, from the equation above,

$$\frac{M}{M'}=\frac{\tan\theta}{\tan\theta'}$$

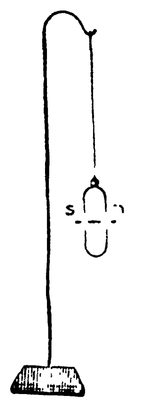


FIG. 219.—The Vibration Magnetometer.

271. Time of Vibration of a Magnet in a Uniform Field.—If a magnet is suspended so that it can turn freely in a magnetic field, and is displaced through a small angle from its equilibrium position, it will be found to vibrate for some time about its position of equilibrium before coming to rest. These vibrations are isochronous—that is to say, each complete vibration takes exactly the same time. The time of one complete vibration of the magnet is given by the formula

$$T=2\pi\sqrt{\frac{K}{M\,.\,H}}$$

where T is the time of vibration, M the magnetic moment of the magnet, H the strength of the field, and K a constant depending on the mass and shape of the magnet, and known as its moment of inertia. It can be calculated for regular solids.

A small magnetic needle suspended by a fine thread of unspun silk, and weighted (to increase the time of vibration), can be used for the comparison of magnetic fields, and is known as the **vibration magnetometer.** A simple form is shown in Fig. 219.

Let T_1 be the time of vibration in a magnetic field of strength H_1, and T_2 that in a field of strength H_2. The time of one vibration can be obtained accurately by finding with a

stop-watch the time taken by the needle in making, say, 50 complete vibrations, and dividing the time taken by the number of swings. Then

$$T_1 = 2\pi\sqrt{\frac{K}{MH_1}}$$

$$T_2 = 2\pi\sqrt{\frac{K}{MH_2}}$$

$$\frac{H_1}{H_2} = \frac{T_2^2}{T_1^2}$$

If we wish to measure the field due to a magnet at a given distance *d* from its centre, we must first find the time of swing in the earth's field H alone. Let it be T_1. Then place the magnet so that its field at the magnetometer needle is parallel to that of the earth and acts in the same direction. Then if F is the field due to the magnet alone, the resultant field on the magnetometer needle is $F+H$; and if T_2 is the corresponding time of swing (which will be less than before) we have, substituting in the equation above,

$$\frac{H}{H+F} = \frac{T_2^2}{T_1^2}$$

$$\therefore\ F = H\left\{\frac{T_2^2}{T_1^2} - 1\right\}$$

If the magnet has been arranged so that F is its field in one of the standard positions, its magnetic moment can be deduced from the formulæ in § 267.

EXAMPLES.

1. What force is exerted upon a magnetic pole of strength 10 units by a pole of strength 36 units at a distance of 6 cms. from it?

2. Two equal magnetic poles are found to repel each other with a force of 16 dynes when placed 2 cms. apart. What is the pole strength?

3. A magnet of magnetic moment 1000 lies in a field of intensity 0·18 gauss. What couple will be required to keep it at an angle of 30° to the direction of the field?

4. Calculate the field due to a bar magnet of moment

2000 at a point on its axis produced at a distance of 40 cms. from the centre of the magnet, using the approximate formula.

5. A bar magnet placed in the "end on" position produces a deflexion of 15° in the needle of a magnetometer when the distance between their centres is 30 cms. What is its moment? If the distance between the poles of the magnet is 6 cms., what is the pole strength? ($H = 0{\cdot}18$ gauss.)

6. Two short bar magnets are placed in turn with their centres 40 cms. distant from the needle of a magnetometer. If the deflexions are respectively 15° and 20°, compare their moments.

7. Two short bar magnets produce the same deflexion on a magnetometer needle when their centres are respectively 20 and 30 cms. distant from the needle. What is the ratio of their magnetic moments?

8. A bar magnet 18 cms. long is placed in the meridian with its N-pole pointing south, and a neutral point is found 30 cms. to the south of the centre of the magnet. If the horizontal component of the earth's field is $0{\cdot}18$ gauss, calculate the pole strength of the magnet.

9. A long bar magnet is placed with its N-pole 10 cms. to the south of a small magnetic needle, and the needle is found to make 50 vibrations in 40 seconds. When vibrating in the earth's field ($0{\cdot}18$ gauss) alone the needle makes 50 vibrations in 80 seconds. Assuming that the S-pole of the magnet is so far away that its effect may be neglected, calculate the strength of the N-pole of the magnet.

CHAPTER III

TERRESTRIAL MAGNETISM

272. Magnetic Declination.—We have already seen that a compass needle at a distance from other magnets sets in a definite direction, to which it returns if displaced. This

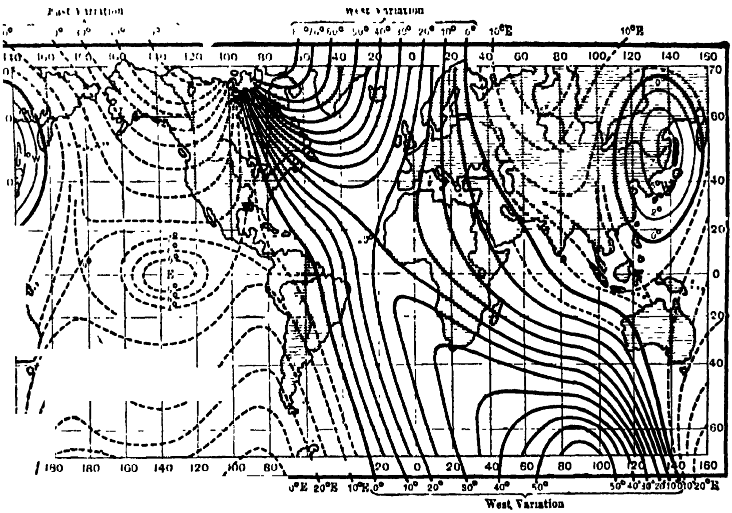


FIG. 220.—Lines of Equal Declination.
(From Sir J. J. Thomson's *Electricity and Magnetism.*)

shows that the needle is in a field of magnetic force, which can only be ascribed to the earth itself. The direction of the compass needle, which is approximately north and south, is known as magnetic north and south. The direction of the axis of the compass needle is the **magnetic meridian** at the place. The angle between the magnetic north and south and the geographical north and south, that is to say, the angle between the magnetic and the geographical meridians,

is known as the **declination.** The declination varies from place to place on the surface of the earth. At present in this country the compass needle points about 17° to the west of the geographical north; the declination is thus about 17° W. The declination decreases as we pass farther east until along a line running approximately north and south, through Finland and Asia Minor, the declination is zero—that is to say, the geographical meridian and the magnetic meridian coincide. *The line joining points where there is no declination* is known as the *agonic* line. At points to the east of this line the declination is to the east.

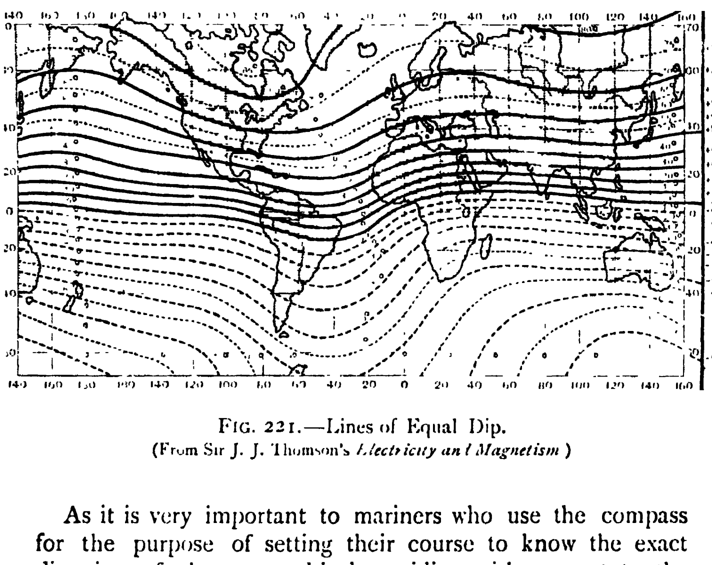


FIG. 221.—Lines of Equal Dip.
(From Sir J. J. Thomson's *Electricity and Magnetism*)

As it is very important to mariners who use the compass for the purpose of setting their course to know the exact direction of the geographical meridian with respect to the compass needle, maps are constructed on which lines are drawn joining up the different places on the earth's surface where the declination is the same. These lines are known as **isogonals.** Such a map is shown in Fig. 220. It will be seen that the isogonals are somewhat irregular in distribution. In addition to the agonic line already mentioned, there is a second one running through the American continent, while a third forms a loop round eastern Siberia. This is known as the Siberian oval.

The declination is not constant, but varies steadily from year to year. At present the declination in this country is decreasing.

273. Magnetic Dip.—A compass needle is only free to turn in a horizontal plane, and therefore only responds to the horizontal component of the earth's magnetic field. Suppose now we suspend a bar of steel by a fine thread from its *centre of gravity. It will be in equilibrium as far as gravitational forces are concerned, and will rest in any position.* Let us now magnetise the bar and suspend it from the same point. It will be found that not only does the bar turn round so as to point in a northerly direction, but its north pole dips downwards towards the earth, the axis of the magnet making a very considerable angle (about 69° in this country) with the horizontal. The total field due to the earth is therefore inclined to the horizontal at a considerable angle.

The angle between the direction of the earth's field and the horizontal is known as the angle of **dip**, *or the* **inclination.**

The inclination or dip varies from place to place on the earth's surface. At a point in Nova Zembla the dip is 90° —that is, the needle points vertically downwards. As we pass farther south the dip gradually decreases, until at places near the Equator the needle sets horizontally, and the dip is zero. A line drawn joining up the places on the earth's surface where the dip is zero is known as the **magnetic equator.** It corresponds roughly with the geographical equator. On passing to the south of the Equator the needle again begins to dip, but this time it is the south pole which points downwards. This southerly dip increases until it reaches 90° at a point in the Antarctic Circle. Lines drawn on a map joining up places of equal dip are known as **isoclinals** (Fig. 221). They are roughly parallel to the geographical lines of latitude.

274. The Earth as a Magnet.—The results we have been considering indicate that the earth behaves like a magnet. If we suppose that the magnetic state of the earth can be represented by a bar magnet beneath its surface, we are able to account in a general way for the phenomena observed. It is obvious that since the north pole of a compass needle is attracted towards the north, that the northern end of this big magnet must be a south pole, and the southern end a north

pole, as marked in Fig. 222. If we draw the lines of force due to such a magnet, then, remembering that a magnetised needle free to move in any direction sets along the lines of force, we see that such a needle would point vertically downwards at a point immediately above the northern end of the magnet, and that the dip would gradually decrease until on the magnetic equator of the magnet the needle would be parallel to the surface of the earth, and the dip consequently zero. South of the Equator the south pole of the needle would begin to dip, the dip increasing until a point was reached immediately above the southern end of the magnet. The main phenomena of the dipping needle are thus reproduced.

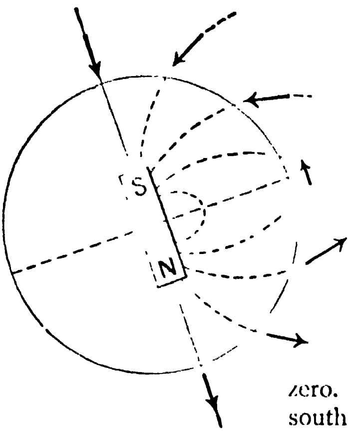


FIG. 222.—The Earth a Magnet.

The magnetic axis of the earth m angle of about 17° with the axis of rotation of the earth. As it cuts the surface in Nova Zembla, to the west of England it is evident that the compass needle which sets along the lines of force will point in this country to the west of the true geographical north.

The values of the various magnetic constants are not constant, but vary gradually from year to year. This seems to be due to a gradual rotation of the magnetic axis of the earth about the geographical axis, a complete rotation occupying about 960 years. The cause of this rotation is unknown.

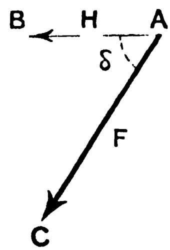


FIG. 223.—Diagram to illustrate Components of the Earth's Field.

275. The Intensity of the Earth's Field.—The earth's horizontal field is only one component of the total field due to the earth. If the plane of the paper in Fig. 223 is the

plane of the magnetic meridian, and if AC represents the direction of the total field due to the earth, and AB the horizontal, then the angle BAC is the angle of dip δ, and it is evident that the horizontal component of the total field F is given by

$$H = F \cos \delta$$

Thus, if H and δ are known, we can calculate F.

The horizontal component of the earth's field requires two experiments for its determination, which are both made with the same magnet. In the first experiment this magnet is used to deflect the needle of an ordinary magnetometer. Then, as before (§ 270), we have

$$M = \tfrac{1}{2}d^3 H \tan \theta$$
$$\frac{M}{H} = \tfrac{1}{2}d^3 \tan \theta$$

where M is the magnetic moment of the magnet and H the horizontal component of the earth's magnetic field. This experiment gives us the ratio $\frac{M}{H}$.

The same magnet is then suspended by a silk fibre so as to turn freely in a horizontal plane. The time T of vibration in the earth's horizontal field is then taken. Then (§ 271)

$$T = 2\pi\sqrt{\frac{K}{MH}}$$
$$MH = \frac{4\pi^2 K}{T^2}$$

We have thus a value for MH. The moment of inertia K of the magnet can be calculated from its mass and dimensions. By dividing the second of these equations by the first a value for H^2 is obtained, and H can thus be calculated.

The value of H increases from the north magnetic pole, where it is of course zero, to the Equator, where its value is about 0·35 gauss. In this country its value is about 0·18 gauss.

276. Measurement of the Dip.—The angle of dip is determined by means of a special instrument known as a **dip circle** (Fig. 224). A long magnetised needle is suspended from a steel axis, driven through it exactly at its centre of gravity. The needle is supported on agate bearings at the centre of a

vertical graduated circle. The circle is turned until it is in the magnetic meridian, and the needle is thus free to turn in the vertical plane containing the magnetic meridian. It therefore sets itself along the lines of the earth's total magnetic field. The angle made by the axis of the needle with the horizontal is the angle of dip.

The simple form of dip circle illustrated in Fig. 224 shows the principle of the dip circle, but a much more elaborate instrument is required if the dip is to be determined with accuracy.

As we have seen, when H and δ are known the total intensity F of the earth's magnetic field is given by $H = F \cos \delta$. The value of F in this country is about 0·48 gauss.

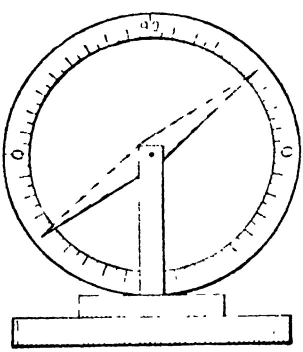


FIG. 224.—Simple Dip Circle.

277. **Magnetisation by the Earth's Field.**—If a long steel bar is held roughly in the direction of the earth's magnetic field (that is, parallel to the dip needle), and struck a few times with a hammer, it will be found to have become magnetised by the induction of the earth's magnetic field. The end pointing towards the north will be a *north* pole, since the pole of the earth to which it is pointing has a south polarity. This phenomenon has important practical bearings. Modern ships are built largely of steel, and the hammering which they undergo in course of construction produces permanent magnetism in the structure. This would have a very serious effect upon the ship's compass if it were not compensated for by fixing other permanent magnets round the compass box in such positions that they produce a field exactly equal and opposite to that due to the magnetism of the ship. The steel girders used in large buildings become magnetised in a similar way, and have a very considerable effect on the magnetic field within the building.

EXAMINATION QUESTIONS.—XIV

1. Give a short account of the most important properties of a magnet.

2. What is meant by the strength of a magnetic pole? How would you show that the poles of a bar magnet were equal in strength but opposite in sign?

3. Describe in detail how you would magnetise a given knitting needle. How would you prove that the needle had become magnetised?

4. What is the molecular theory of magnetism? Describe experiments in support of it.

5. What is the magnetic moment of a magnet? How would you compare the magnetic moments of two magnets?

6. How is the strength of a magnetic field defined? Describe an instrument for comparing the strengths of two magnetic fields, and explain how it can be used for comparing the field strengths at different distances along the axis produced of a bar magnet.

7. A short magnet is placed in a horizontal plane with its axis in the meridian and its north-seeking pole pointing south. It is found that at a point on the axis 20 cms. to the south of its mid-point the resultant field is zero. If the horizontal component of the earth's magnetic field is 0·20 dyne per unit pole (gauss), what is the magnetic moment of the magnet?

8. Explain what is meant by a line of force. Why do lines of force never cross? Draw a diagram of the lines of force near a bar magnet placed in the magnetic meridian with its north pole pointing south.

9. Sketch the general form of the lines of force due to a bar magnet, and point out how the actual form of the lines is modified by the earth's magnetic field when the magnet is placed in an east and west position.

10. What reasons are there for stating that the earth is magnetised? State what you know of the distribution of this magnetism.

11. What is meant by magnetic dip? Give a general account of the way in which the dip varies over the surface of the earth.

12. Describe a vibration magnetometer, and explain how it is used to compare the strengths of two magnetic fields. A magnetic needle makes one complete oscillation in four seconds at a place in England where the value of H is 0·20 gauss. What will be the value of H at a station where the same needle makes one oscillation in three seconds?

CHAPTER IV

ELECTRICAL CHARGES—ELECTRIC INDUCTION

278. Electrical Attractions.—If a stick of ebonite or sealing-wax is rubbed with flannel it is found to attract small pieces of paper, feathers, pith balls, and other similar light objects. The rod is said to have become *electrified*, or to have acquired a *charge of electricity*. The attraction of the rod for the paper is called electrical attraction, and is said to be due to the presence on the rod of a charge of electricity. The property is not confined to ebonite and sealing-wax. Under proper conditions any body can be electrified by friction with a suitable rubber.

279. Two Kinds of Electrification.—If an ebonite rod is electrified by friction and suspended horizontally by a silk thread so as to be free to turn, and if a second ebonite rod electrified in the same way is brought near one end of the first, it will be found that the two rods repel each other, the suspended rod turning away from the other. If, however, a glass rod is rubbed with silk and brought near the end of the suspended charged ebonite rod, it will be seen that the ebonite is attracted by the charge on the glass. *There are thus two kinds of electricity*, as there are two kinds of magnetic poles.

Like electrical charges repel; unlike electrical charges attract each other.

The law is thus the same as for magnetic poles.

The kind of electricity excited on a glass rod when rubbed with silk was called *vitreous* electricity, while that excited on ebonite or sealing-wax by flannel was termed *resinous*. These names are obsolete. It was found that if equal charges of vitreous and resinous electricity were transferred to the same body, the body showed no signs of any electrification. The two electricities exactly neutralised each other, and the result-

ing charge was zero. Hence, by analogy with the mathematical symbols plus and minus, the two electricities were called *positive* and *negative* respectively, since the addition of two equal but opposite charges produces a zero charge, just as the sum of two equal positive and negative numbers is zero. The *vitreous* electricity is termed **positive** (+) and the *resinous*, **negative** (−). The choice was perfectly arbitrary. Charges of like sign repel each other, charges of unlike sign attract each other. Charges of either sign will attract uncharged objects.

280. Conductors and Insulators.—If a brass rod is held in the hand and rubbed with flannel, it will show no signs of electrification. If, however, the brass rod is fitted with an ebonite handle by which it can be held, so that no part of the hand comes in contact with the brass, the brass rod becomes strongly electrified when rubbed with the flannel. The cause of this is not far to seek. Let us touch the brass rod, while so electrified, with the hand. The charge at once disappears. Similarly, if we touch the brass rod with a piece of metal of any kind, a damp cloth, or a stick of charcoal, the charge at once disappears. If, however, we touch the charged rod with ebonite, sulphur, wax, or dry silk, the rod remains charged. Thus substances may be divided into two classes, according as they do or do not permit electricity to escape through them. Substances which allow the electricity to pass through them are called **conductors**; those which prevent its passage, or allow it to pass only very slowly through them, are termed **non-conductors**, or, more usually, **insulators**. All metals, charcoal, water, the human body, etc., are conductors; sulphur, ebonite, dry glass, rubber, wax, shellac, etc., are insulators. It is obvious that the air is also an insulator, since a rod surrounded by air does not immediately lose its charge.

The difference between insulators and conductors, although often very marked, is only one of degree. The best conductors offer some resistance to the passage of the electricity, while even the best insulators allow electricity to pass through them slowly.

A body is said to be insulated if it is completely surrounded by non-conductors. Since the air is a very good insulator, a body will be insulated if it is supported on a plate of non-conducting material or fixed on a non-conducting stem, as in the case of the brass rod already considered. Sulphur is one

of the best insulators known, but has the disadvantage of being brittle. Ebonite, if its surface is clean, is very efficient and convenient. The glass stems covered with varnish, commonly used in the older electrical apparatus, were very unsatisfactory owing to the tendency for a conducting film of moisture to form on the surface.

A body which is connected to the ground by a conductor is said to be *earth-connected*, or *earthed*. The earth, the conducting wire, and the body then form part of one continuous conductor, over the whole of which the electrical charge on the body can spread. Since the earth is very large compared with the electrified body, the fraction of the original charge which remains on the body after earthing is infinitesimal. Practically the whole charge flows to earth, along the conducting path, and the body is *discharged*.

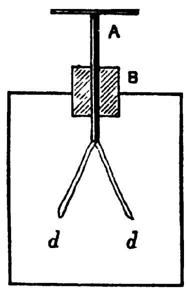


FIG. 225.—The Gold-Leaf Electroscope.

A body can be efficiently earthed by connecting it to the water-pipes by means of a conducting wire. For most purposes the body can be sufficiently well earthed by touching it with the hand, the human body being a conductor of electricity.

Thus, when a brass rod held in the hand is rubbed, the electricity generated on it passes immediately through the hand to the earth, and for this reason the rod appears uncharged when tested. To obtain a charge on a conductor by rubbing, it is necessary to hold it by an insulating support.

281. Electroscopes.—An instrument for detecting electrical charges is called an **electroscope.** Thus the suspended charged ebonite rod of § 279 is a simple but inconvenient form of electroscope.

The gold-leaf electroscope is a more convenient instrument. A brass rod A (Fig. 225) passes through an insulating stopper B (preferably of sulphur or ebonite) into a box C, the front and back of which are made of glass so that the interior can be observed. The sides of the box are lined with tinfoil, which should be earth-connected (the laboratory bench will generally be a good enough connector). Two strips of gold leaf ***d***, ***d*** are mounted at the lower end of the rod, and hang down

side by side when the rod is uncharged. If a charge is given to the upper surface of the rod (which usually takes the form of a flat brass plate or a brass knob), the charge spreads to all parts of the rod and the gold leaves. The latter, therefore, being similarly charged, repel each other and stand apart as shown in the figure, the magnitude of the divergence being a rough measure of the strength of the charge on the leaves. The instrument can thus be used for detecting electrical charges.

If we charge an electroscope by rubbing the upper plate with a charged ebonite rod, the charge on the electroscope will be of the same sign as that on the rod—that is, negative. If another negatively charged rod is now brought near the cap of the electroscope, the leaves will diverge still more. If, however, a positively charged body (*e.g.* a rubbed glass rod) is brought near the cap the leaves will collapse. An electroscope can thus be used to determine not merely the presence but also the sign of an electrical charge. If the electroscope is charged negatively, an increase in the divergence of the leaves indicates the presence of a negative charge: if it is positively charged, an increase in the divergence indicates the presence of a positive charge.

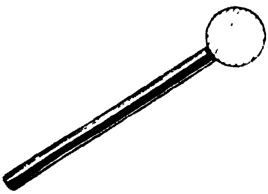


FIG. 226.—Proof Plane

A collapse of the leaves may, as we have seen, indicate the presence of a charge of opposite sign to that on the instrument, *but is not in itself conclusive.* If an earth connected conductor is brought near the cap of an electroscope charged with either sign, it will be found that the leaves collapse. *The only sure test for the presence of a charge of given sign is to obtain an increase in the divergence of the leaves of a suitably charged electroscope.*

A body may be too highly charged to be brought near an electroscope with safety, or it may be of such a size as to be inconvenient to move. In this case a proof plane may be used. A proof plane consists of a conducting metal disk (Fig. 226) mounted on an insulating handle. The disk is placed in contact with the body whose electrification is to be tested, and takes some of its charge. The proof plane is then brought near the electroscope, and the sign of its charge

tested in the usual way. This will be the sign of the charge on the body.

282. Electrical Induction.—A body, as we have seen, may become electrified by actual contact with another electrified body. In this case the charge is shared between the two bodies, the charge gained by the one body being lost by the other. This may be termed electrification by conduction. It is possible, however, to obtain a charge on a conductor, by the action of another charged body, without the latter losing any of its charge. Suppose an insulated positively charged sphere A is brought near one end of an insulated elongated conductor such as BC (Fig. 227), it will be found that the end B nearest the positive charge A acquires a negative charge, while the end C becomes positively charged. These statements can readily be tested by means of an electroscope and proof plane. If, without touching BC, the charge A is withdrawn, BC will be found to be uncharged.

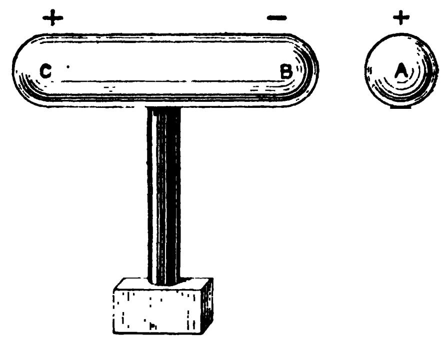


FIG. 227.—Experiment to illustrate Electrical Induction.

These results are conveniently explained by assuming that an uncharged conductor contains indefinitely large but equal charges of positive and negative electricity. Since the charges are equal and opposite they neutralise each other, and the conductor as a whole has no electrical action. When, however, the charged body A is brought near one end of the conductor, it attracts the negative charge within the conductor and repels the positive, and, as the charges are free to move, the end B becomes negatively and the end C positively charged. This process is known as **induction**, and may be compared with magnetic induction.

Thus, if a charge of electricity is brought near an insulated conductor, a charge of electricity of opposite sign will be induced on those portions near the inducing charge, while the

portions farther away will become charged with electricity of the same sign as the inducing charge.

These induced charges disappear when the inducing charge is removed, providing that the conductor remains insulated throughout the experiment. It follows, therefore, that the induced charges were opposite in sign but equal in amount. Suppose, however, that while the charge A is in position, the conductor BC is earthed, by touching it with the finger. The earth and BC now form part of one big conductor. The negative charge is again induced on the portion B of this conductor near A, while the positive charge is induced on the portions most remote—that is, on the earth itself. If the earth connection is now broken (without removing A) the negative charge on BC is separated from the positive charge which has gone to earth. The two charges, there-

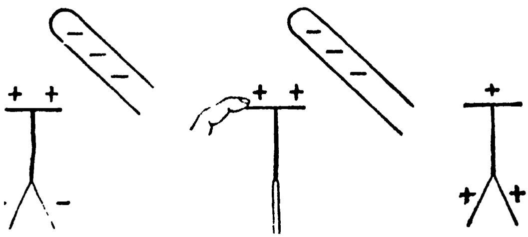


FIG. 228.—Charging an Electroscope by Induction.

fore, can no longer recombine when A is withdrawn. The conductor BC is thus left with a permanent negative charge, which has been produced by induction without any decrease in the positive charge on A.

The process of induction is the most convenient way of charging an electroscope. Bring up near the cap of the electroscope a negatively charged rod. The leaves diverge with negative electricity, while the cap which is nearer the inducing charge becomes positively charged. While the rod is near the electroscope touch the cap of the electroscope with the finger for a moment. The leaves collapse since the charge upon them now goes to earth. Withdraw the finger, leaving the electroscope insulated, and then withdraw the charged rod. The electroscope will be left with a charge of opposite sign to that of the rod. These operations are indicated diagrammatically in Fig. 228. Thus, to charge an

electroscope positively by induction, we use an ebonite rod; while to charge it negatively by induction we use a rubbed glass rod.

283. Faraday's Ice-Pail Experiments.—The process of electrostatic induction was investigated by Faraday. Let us stand a tall tin can (Fig. 229) on the cap of our electroscope, which we will suppose to be discharged. In Faraday's original experiments an ice pail was used—hence the name of the experiment.

1. Introduce inside the can an insulated metal ball carrying, say, a positive charge. The leaves of the electroscope will diverge with a charge which can be shown to be positive by bringing a positively charged rod near the cap of the electroscope. Move the ball about in the can without touching the sides. The divergence of the leaves remains the same. Withdraw the ball without touching the can. The leaves collapse. On testing the ball it will be found to have retained its charge. The positive charge on the ball induces a negative charge on the inner walls of the vessel and a positive charge on the outer wall which charges the gold leaves. These results were to be expected from our previous experiment. We learn, however, further that when the inducing charge is practically completely surrounded by a metal vessel (as in the present experiments) the magnitude of the induced charge is independent of the position of the ball within the vessel.

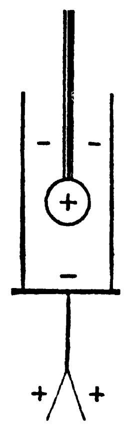


FIG. 229.—Faraday's Ice-Pail Experiment.

2. Introduce the charged metal ball as before, and while it is still in the can, earth the can for a moment by touching it with the finger. The leaves collapse. On withdrawing the ball the leaves diverge again to exactly the same extent as before, but this time the sign of the charge is negative. The positive charge has passed to earth, leaving only the induced negative charge on the can. Since the divergence on withdrawing the ball is the same as before, the negative induced charge is exactly equal to the positive induced charge.

3. Discharge the electroscope, and again introduce the positive charged ball. Now allow it to touch the sides of the can. The divergence of the leaves is quite unaffected by the

contact. On withdrawing the ball the leaves still retain their divergence, but on testing the ball it will be found to be completely discharged. The positive charge on the ball has been exactly neutralised by the negative induced charge on the walls of the can. Hence we have this important result:

If a charge is introduced into the interior of a closed conducting vessel, the induced charges are equal in magnitude to the inducing charge.

In the case of a conductor which does not surround the inducing charge, the induced charge upon the conductor will be less than the inducing charge. A few experiments on charging an electroscope by induction will show that the induced charge produced on the leaves becomes greater the closer the inducing rod is held to the electroscope. This, however, is not a contradiction of the law. The total charge induced by the electrified rod is equal to the charge upon the rod itself, but it is not all concentrated on the electroscope. Charges are induced by the rod on all neighbouring conductors, *e.g.*, on the walls, ceiling, and floor of the room. If we could collect all these induced charges we should find that they were equal to the charge on the rod. If the rod is brought nearer to the electroscope a greater amount of the charge is induced on the latter and less on other conductors. Hence the increased divergence of the leaves.

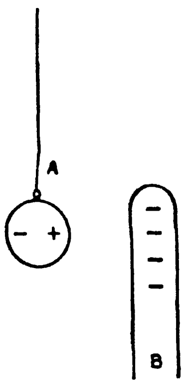


FIG. 230.—Attraction of an Uncharged Body.

284. Attraction of Uncharged Bodies.—The attraction of uncharged bodies by an electric charge is an induction effect. Consider a small pith ball A (Fig. 230) near a negatively charged rod B. The negative charge on B induces a positive charge on the side of the ball nearest the rod, and a negative charge on the farther side. These charges are equal in magnitude, but since the positive charge is nearer to the rod than the negative, the force of attraction between the negative and positive charges is greater than the force of repulsion between the two negative charges, and the ball is attracted to the rod. The action is therefore similar to the attraction of a piece of unmagnetised iron by a magnet (§ 254).

285. The Charge on a Conductor lies on the Surface.—Electrify a hollow metal cylinder (one of the tall cans used in the ice-pail experiments will do) as strongly as possible, and test the electrical condition of the different parts by means of a proof plane and electroscope. It will be found that a charge can be collected by the plane from all parts of the outer surface of the can, but that when the inside of the can is tested by the plane no charge at al is carried away by it. The charge resides entirely on the outer surface.

This fact was demonstrated by Faraday in a rather interesting way. He made a box sufficiently large to contain himself and his electrical measuring instruments. The box was made conducting by covering its surface completely with copper wire and tinfoil, and was insulated from the ground by glass stands. Faraday entered the box, which was then charged by a large electrical machine so that sparks of considerable length could be taken from any part of its surface. In the interior, however, not the slightest electrical effect could be detected, and the sensitive electroscopes inside the box were quite undisturbed by the great electrical forces without. The whole of the electrical effect was confined to the exterior of the box. The statement that there is no charge on the inner surface oi a closed conductor is only true if there are no charged bodies inside it, which are insulated from it. Thus, as we have seen, when a positively charged ball is held inside a tall metal can there is an induced negative charge on the inner walls of the can. If, however, the ball is placed in contact with the inner surface of the can so that the two form part of the same conductor, it will be found on taking it out, that it is completely discharged; the whole of the charge having passed from it to the outer surface of the can.

286. Distribution of Charge on the Surface of a Conductor.—If an insulated pear-shaped conductor (Fig. 231*a*) is charged, and the state of electrification tested in the usual way with a proof plane, it will be found that the plane collects a greater charge from the pointed end A than from the broad end B. *The amount of charge on unit area of a surface is known as the surface density of electrification.* Thus the surface density is greater at the sharp end A than at the broad end B. We may represent the surface density on a conductor by drawing dotted lines round it so that the distance of the dotted line from the conductor at every point is proportional

to the surface density at that point. It is found that the surface density becomes very great at places where the

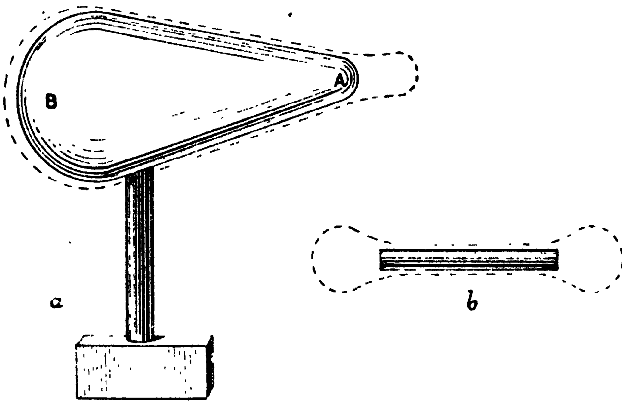


FIG. 231.—Diagram to show Distribution of a Charge on the Surface of a Conductor.

curvature of the surface is large—for example, at the point A of the conductor AB, at the edge of a flat disk (Fig. 231*b*), and above all at a sharp point. The density at a sharp point becomes so great that it breaks down the insulation of the air around it, and so allows the conductor to discharge itself. On account of this discharging action of a point, conductors which are intended to retain a charge should be made as smooth as possible, and no projecting parts or points should be allowed.

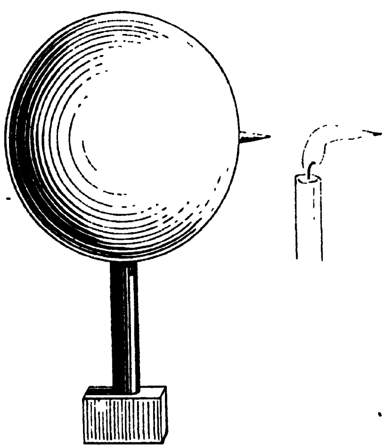


FIG. 232.—Discharging Action of a Point.

If a needle point (Fig. 232) is attached to a charged conductor, a candle flame held near the point will be blown

away from the point, showing that a strong current of air is flowing from the point away from the conductor. This current consists of a stream of particles of air which have become charged by the electrical forces near the point, and are then repelled by the charge remaining on the conductor. It is this stream of electrified particles which discharges the conductor.

CHAPTER V

FORCE BETWEEN ELECTRICAL CHARGES—LINES OF FORCE

287. Law of Force between Electrical Charges.—The mechanical force between two electrical charges was investigated by Coulomb. It is evident that we cannot experiment with electrical charges, but only with charged bodies. Now the charge distributes itself over the whole of the surface of the bodies, and all parts of the two charges are not at the same distance apart. Hence the force between two charged bodies will depend on their shape and size as well as on their charges and the distance between them. If, however, the bodies are small compared with the distance between them, we can regard each charge as being situated practically at a single point, at the centre of the small body. The charges are then known as **point charges.**

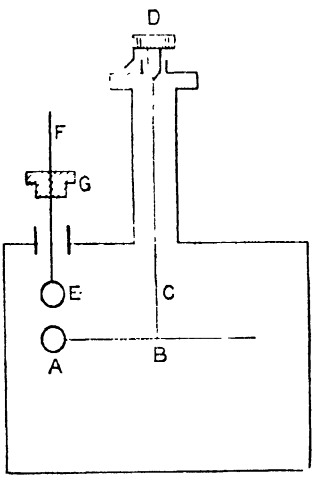


FIG. 233 Coulomb's Torsion Balance.

The mechanical force between two point charges varies inversely as the square of the distance between them.

The law of force for point charges is thus the same as for magnetic poles.

This law of force was propounded by *Coulomb* from experiments made by him with a torsion balance. An insulating rod of shellac (Fig. 233) having a small gilt pith ball A at

one end is supported by means of a fine wire from a movable torsion head D, the whole being enclosed in a cylindrical glass vessel to avoid draughts. A second similar gilt pith ball E is supported by a second shellac rod F, passing through a cork G. When the cork is fitted into its place the two pith balls are in the same horizontal plane. The pith ball E is given a charge, and the torsion head D is turned until the two balls touch. They share the charge between them by conduction, and as the charges in the two balls are thus of the same sign A is repelled to some distance from E. This distance is measured, and also the twist on the supporting wire. The torsion head D is then turned until the distance between the balls is reduced to one half. It is found that to produce this decrease the twist on the wire must be increased fourfold. Now it is known that the couple exerted by a twisted wire is directly proportional to the twist upon it. Thus the force between the two charges is increased fourfold when the distance between them is halved—that is, the force is inversely proportional to the square of the distance between the charges.

These experiments are necessarily inaccurate owing, among other causes, to the gradual leakage of the charges during the experiment. Our belief in the accuracy of the inverse square law rests on Faraday's discovery that there is no electrical force inside a closed conductor. It can be shown mathematically that this result is only true if the law of force between two electrical point charges is that of the inverse square.

288. Unit of Electrical Charge.—The mechanical force between two charged bodies increases with the charge upon them. Following the line of argument employed in the case of magnetic poles, we may define our unit of electrical charge as follows:

Unit electrical charge is one which if placed at a distance of 1 cm. in air from an equal and similar charge will repel it with a force of 1 dyne.

Taking this definition of unit charge, it follows that if F is the mechanical force between two charges of electricity of magnitude q and q' respectively separated in air by a distance of d cms., then

$$F = \frac{qq'}{d^2} \text{ dynes}$$

If the two charges are like, the force will be one of repulsion, if unlike, the charges will be one of attraction. Now a charge of 10 units of positive electricity may be represented by the symbol $+10$; while a charge of 10 units of negative electricity will be represented by the symbol -10. Taking the symbols $+$ and $-$ in their usual algebraical sense, it will be seen that the product of two *like* charges is always *positive*, while the product of two unlike charges is negative. The force between two charges will therefore have a positive sign if the charges are like, and a negative sign if they are unlike. Thus a positive value of the force indicates a force of repulsion, a negative value of the force indicates a force of attraction.

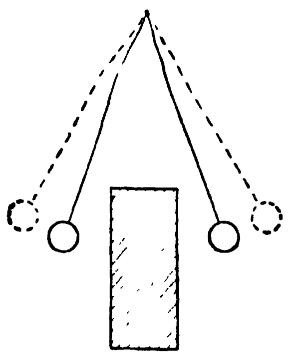


FIG. 234.—Experiment to illustrate the Effect of the Medium on the Force between the Charges.

The presence of a charge on a body is regarded as being due to the presence on the body of a quantity of something called electricity. A unit electrical charge may be regarded as indicating the presence of unit quantity of electricity upon the body. Hence—

Unit quantity of electricity is that quantity which if placed at unit distance in air from an equal and similar quantity will repel it with a force of 1 dyne.

Electrical charge and quantity of electricity are used as interchangeable terms.

289. Effect of the Medium on the Force between Charges.—We have specified in our definition above that the charges are to be separated by air. It is found that the force between two given charges depends very largely on the nature of the substance between them. If two pith balls are suspended by silk threads and given a charge, they will diverge. If now a thick slab of glass or sulphur (Fig. 234) is placed between them, the divergence will be considerably diminished. On withdrawing the slab, the balls fly apart again to their original position. Thus, while the charges remain the same, the force between them is appreciably lessened when glass or sulphur is substituted for air as the medium between the charges.

In general, therefore, the force F between two charges q and q' separated by a distance d in any medium may be expressed by the formula

$$F = \frac{1}{K}\frac{qq'}{d^2} \text{ dynes.}$$

where K is a constant which depends on the nature of the medium between the two charges.

Faraday, who was the first to point out the importance of the medium between the charges in electrical phenomena, called the constant K the *specific inductive capacity* of the medium. It is also known as the *dielectric constant.* The greater the value of the specific inductive capacity *the smaller* the force. The specific inductive capacity of air is taken as *unity. The specific inductive capacity of glass is about 6*; that of sulphur, 4; and that of water nearly 80. The force between two given charges separated by water is therefore only $\frac{1}{80}$th of the force between the same charges when separated by the same distance in air.

290. Electrical Field—Intensity.—*Any region in which electrical force is manifested is known as a field of electric force, or simply as an* **electric field.** The strength of the field is defined in the same way as the strength of a magnetic field.

The field at a given point is said to be of unit strength if a unit charge placed at the point would experience a mechanical force due to the field equal to 1 dyne.

The strength of an electric field is often known as the **electric intensity,** and will be denoted by the letter R. Thus a charge q when placed in a field of intensity R will experience a force F given by

$$F = qR \text{ dynes.}$$

291. Lines of Force.—An electric field can be represented by a system of lines of force in exactly the same way as a magnetic field (§ 264).

A line of force in an electric field is a curve such that the direction of the resultant field at every point on the curve is along the tangent to the curve at that point.

A small conducting thread (a piece of cotton fluff, for example) will set itself along the lines of an electric field in the same way as an iron filing sets in a magnetic field, and for a similar reason. Owing to the experimental difficulties

electric fields cannot be mapped out experimentally with any accuracy. The direction of the lines of force can be deduced mathematically in simple cases. Fig. 235 represents the lines of force in the electric field due (*a*) to a single point charge, (*b*) to two equal and opposite charges, and (*c*) to two equal and similar charges.

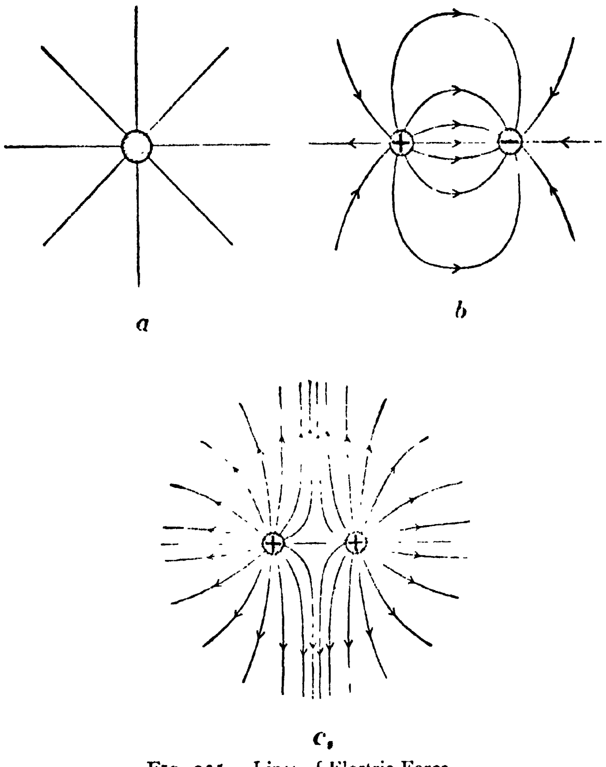


FIG. 235.—Lines of Electric Force.

A line of force will commence on a positive charge and must terminate on a negative charge. It is usual to regard one line of force as arising from each unit of positive charge, and ending on a unit of negative charge. It can be shown that the number of lines of force passing through unit area drawn at right angles to the direction of the lines at any

point in the field will in this case be directly proportional to electric intensity at that point. They afford, therefore, a measure not only of the direction of the field at all points in it, but also of the strength of the field at any point. A map drawn in this way represents the field completely both in magnitude and direction.

Faraday, to whom the idea of lines of force is due, showed that all actions between electrified bodies could be completely accounted for if it was supposed—

(*a*) that the lines of force tended to shorten themselves, as if they were stretched elastic cords;

(*b*) that neighbouring lines of force exerted a lateral repulsion on each other.

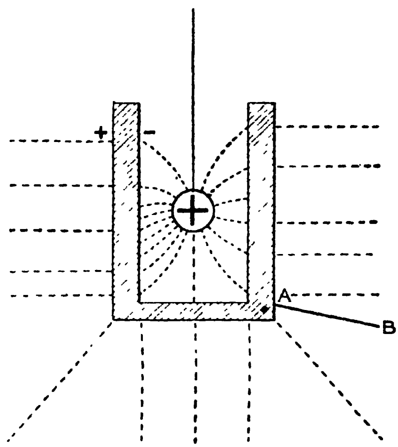


FIG. 236.—Lines of Force and Induction—Ice-Pail Experiment.

This idea has proved very useful, and modern science has tended to endow these lines of electric force (or Faraday tubes, as they are often called) with a real existence.

We have only space to illustrate the method here. For example, in the case in Fig. 235*b*, the lines of force joining the two charges will tend to shorten, and also will tend to repel each other in a direction at right angles to their length. For each of these reasons there will be a force on the two bodies tending to draw them closer together—that is to say, the two unlike charges will attract each other. On the other hand, in Fig. 235*c* there are no lines of force passing from one charge to the other. The mutual repulsion of the lines of force running parallel to each other up the centre of the field of force will, however, tend to urge the two bodies apart; and the tendency to shorten of the lines running in opposite directions from the charged bodies which end on negative charges

induced on the walls and floor of the room will have a like effect—that is to say, the two positive charges will tend to move apart.

292. Lines of Force and Electrical Induction.—Since there is no field inside a closed conductor, there are no lines of force. A line of force ends when it falls on a conducting surface. Thus, if a positively charged sphere is placed in a metal vessel the system of lines of force which originally radiated from the sphere to the walls of the room will be cut by the walls of the vessel, as shown in Fig. 236. Since the termination of a line of force implies a unit negative charge, while its commencement implies a unit positive charge, it is

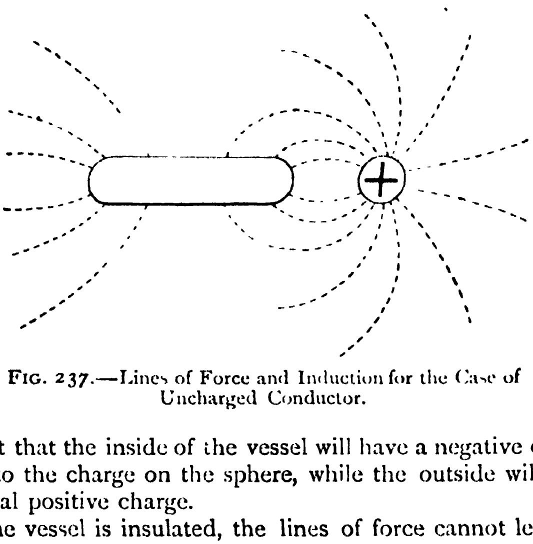


FIG. 237.—Lines of Force and Induction for the Case of Uncharged Conductor.

evident that the inside of the vessel will have a negative charge equal to the charge on the sphere, while the outside will have an equal positive charge.

If the vessel is insulated, the lines of force cannot leave it. If, however, the vessel is connected to the walls of the room, say by a conducting wire, the ends of the lines of force running from the vessel to the walls of the room will be free to move along the conducting wire. Thus if the vessel and the walls of the room are joined by a wire AB, the lines of force nearest AB will, owing to the repulsion of the lines beyond them, be driven into AB and will disappear. Since the other lines of force were kept in equilibrium by the lines which have now disappeared, they also will be repelled into the wire and will disappear. Thus the whole field between

the vessel and the walls will vanish, and we shall be left with the negative charge on the inside of the vessel, and the positive charge on the sphere. If the latter is now withdrawn the vessel will be left with a negative charge. Faraday's conception of lines of force thus gives an adequate representation of the process of electric induction.

In the case where a charged sphere is brought near

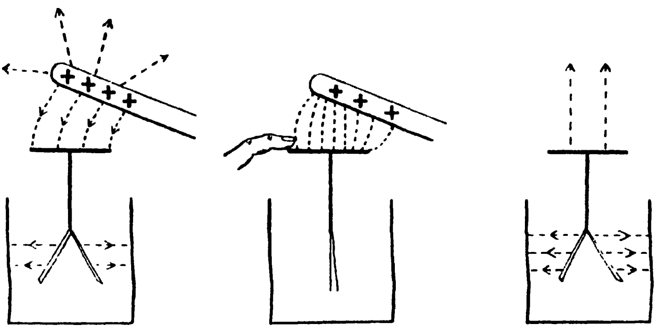


FIG. 238.—Lines of Force during the Charging of an Electroscope by Induction.

another conductor, only a fraction of the lines of force from the sphere are cut by the conductor (Fig. 237), the remainder finding their way directly to the walls of the room. Thus the induced charge on the conductor will only be a fraction of that on the sphere.

The process of charging an electroscope by induction may be left as an exercise to the student. The diagrams for the different stages are given in Fig. 238.

CHAPTER VI

ELECTRICAL POTENTIAL AND CAPACITY

293. Potential.—If a positively charged conductor is brought into contact with an uncharged conductor, electricity will pass from the former to the latter. But it is quite easy to show that if two positively charged conductors are placed in contact one will in general gain a further charge at the expense of the other. It can be shown that it is not invariably the ball which has the bigger charge which parts with some of its charge to the other. It is easy to arrange the experiment so that the ball having the smaller charge gives up electricity to the more highly charged ball. What then is the property which determines the direction in which the transference of electricity will take place when two bodies are placed in electrical contact?

We have already considered a similar problem in the case of the transference of heat (§ 96). One body, such as a red-hot needle, will give up heat to another, such as a bucket of warm water, although the heat in the latter is much greater than that in the needle. The property which determines the direction of the flow of heat is temperature. *The property which determines the direction of flow of electricity is known as* **potential,** *or* **electro-motive force.**

Potential in electricity is thus analogous to temperature in heat. The analogy between the level of a water supply and the temperature (§ 96), therefore, applies equally to potential, and should be carefully studied. Potential, in other words, is electrical level. A sphere charged to a high potential will part with electricity to one at a low potential, irrespective of the quantities of electricity in the two bodies. It has been agreed in problems on potential to consider the changes as being brought about by the transference of *positive* electricity. Thus, if a positively charged conductor is connected to earth, the positive electricity will flow to earth because the potential of

the conductor is greater than that of the earth. Similarly, positive electricity will flow from the earth to a negatively charged conductor, because the potential of the conductor, which in this case is negative, is lower than the potential of the earth.

On the other hand, electricity will not flow from one place to another at the same potential, no matter what the charges may be.

Thus in the induction experiment in § 282, although one end of the conductor has a positive charge and the other a negative charge, the two charges do not recombine although situated on a conducting surface, because the potential of this surface is the same throughout. Similarly, if the conductor is earthed either at the positive or the negative end, positive electricity will flow from the conductor to the earth because the potential of the conductor is higher than that of the earth.

It must be noticed that a negative charge does not necessarily imply a negative potential. The negative charge on the conductor we have been considering is at a positive potential. Potential is simply what we have defined it to be—the electrical condition which determines the direction in which positive electricity will flow.

294. Measurement of Potential.—This definition does not give us a means of measuring potential. The analogy with water-level and the flow of water will help us here. The work which must be done to move a given quantity of water from a lower to a higher level is equal to the weight of the water multiplied by the difference in the levels (§ 36). Thus we could have defined difference in level not in units of length, but by the work which must be done to move unit mass from the lower to the higher level. This is the method adopted in measuring electrical level.

The difference of potential between two points is the work which must be done to move unit quantity of positive electricity from the one point to the other against the electrical forces.

Unit difference of potential exists between two points if 1 *erg of work is done in moving a unit positive charge from the one point to the other against the electrical forces.*

If work has to be done to move a *positive* charge from A to B, then B is said to be at a higher potential than A.

If V and V′ are the potentials of the two points, and w the work done in moving a unit positive charge from A to B, then

$$V' - V = w$$

295. Equipotential Surfaces.—*A surface drawn to pass through all points in the field which have the same potential is called an* **equipotential surface.** It follows from the definition there is no tendency for electricity to pass from one point to another on the same equipotential surface. Hence the electrical forces have no component along such a surface, and *the lines of force cut the equipotential surface at right angles.*

The surface of a conductor is an equipotential surface. For since electricity is free to flow in any direction over the surface of a conductor, if one point on the surface were at a higher potential than another the electricity there would flow down the potential gradient until the difference was neutralised. This result is very important.

Similarly, since there is no field inside a closed conductor there is no work done in moving a charge from one point to another inside it. Thus the whole of the surface and interior of a closed conductor are at the same potential.

296. Zero of Potential.—Our definition only enables us to measure differences of potential. In practice it is usual to regard the earth, and in consequence any conductor in electrical contact with it, as having zero potential, in the same way that the mean sea-level is taken as the zero in measuring heights. The earth is so large that our largest electrical operations cannot be regarded as sensibly affecting its potential. It thus affords a constant and easily accessible standard. Potentials higher than that of the earth are taken as positive, those lower than that of the earth as negative. An earth-connected conductor is at zero potential under all circumstances.

297. Relation between Potential and Intensity.—If the electric field between two points is uniform, their difference of potential can be calculated in terms of the intensity. Let R be the intensity and d the distance apart of the points. The mechanical force on unit charge placed in the field is by definition R, and the work done in moving the charge a distance d parallel to the direction of the field is therefore R . d. But by definition this work measures the difference of potential between the points. Hence—

$$V - V' = R \, . \, d$$

and, conversely,

$$R = \frac{V - V'}{d}$$

If the unit positive charge is moved in the opposite direction to the lines of force, work must be done on the charge to move it. If the charge is moved in the direction of the lines of force, that is in the direction in which it is urged by the electrical forces, work will be done by the electrical forces upon the charge. In the former case the work is considered positive, in the latter negative.

298. Practical Measurement of Potential.—Potential differences can be measured by a gold-leaf electroscope. We have so far used the electroscope for measuring charges, but in reality the divergence of the leaves indicates not charge but potential difference. When the gold leaves are charged there is a potential difference between the leaves and the case (which is at zero potential, being earthed), and consequently a field of force between the leaves and the case. The lines of this field tend to shorten, and hence the leaves are drawn apart. That this explanation is correct can easily be verified by insulating the electroscope on a slab of wax, and connecting the case to the leaves. However highly the instrument may be charged, there will be no divergence of the leaves under these circumstances.

Now by the preceding section the greater the potential of the leaves, the greater will be the field between them and the case, and hence the greater the divergence of the leaves. Thus the divergence of the leaves is a measure of their potential.

To measure the potential of a conductor, therefore, we place it in electrical contact with the cap of an electroscope, by means of a conducting wire. The conductor, the wire, and the leaves of the electroscope now form part of the same conductor, and hence are all at the same potential (§ 295). Thus the divergence of the leaves is a measure of the potential of the conductor.

The use of the electroscope for measuring charges depends on the fact that for a given conductor the greater the charge upon it the higher its potential. Thus, if we convey a charge from a given charged body to an electroscope by means of a proof plane, the potential of the electroscope will be proportional to the charge given to it by the proof plane, and hence the divergence of the leaves will be a measure of this charge. If, however, we connect the electroscope direct to the charged body, the potential of the gold leaves will be that

of the body, and the divergence of the leaves will measure not the charge on the body, but its potential.

299. Electrometers.—*An instrument for measuring a difference of potential is known as an* **electrometer.** The gold-leaf electroscope can be used as a simple electrometer by placing a graduated scale behind the gold leaves. The divergence of the leaves increases with the difference of potential between the leaves and the case. The relation is not a simple one, and the instrument has to be graduated empirically. Modifications of the gold-leaf electroscope, however, are of great use as electrometers for certain purposes.

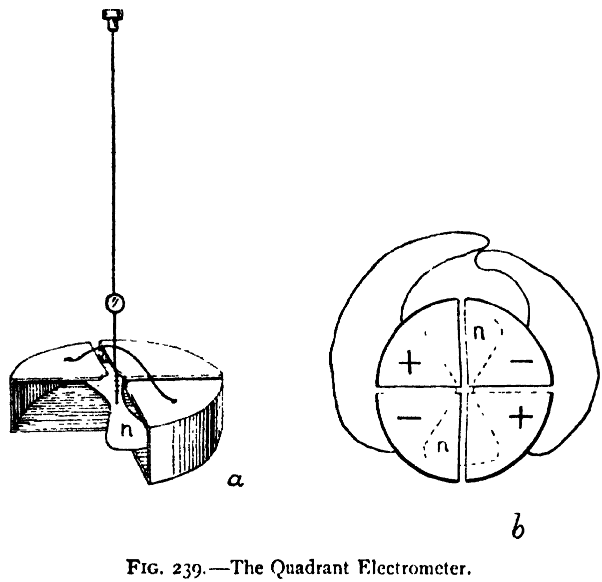


FIG. 239.—The Quadrant Electrometer.

Another form of electrometer, known as the **quadrant electrometer**, is the one generally used for accurate work. The quadrant electrometer (Fig. 239) consists of four quadrant-shaped boxes of equal size, such as might be produced by sawing a shallow brass cylindrical box into quadrants by two cuts along two diameters at right angles. The separate quadrants are thus insulated from each other, and are supported on separate insulating stems of ebonite or amber. The two opposite pairs of quadrants are, however, joined together by

copper wires as shown in the figure. A light aluminium plate, known as the needle, and shaped as shown in the figure, is suspended symmetrically inside the box, by means of a fine conducting wire, so that its long axis is parallel to one of the divisions between the quadrants. In the diagram one of the quadrants has been removed in order to show the needle more clearly.

To measure a difference of potential, the needle is charged to a constant high potential, say positive. If the needle is hanging symmetrically inside the box, there will be no tendency for it to be deflected in one direction rather than the other if the quadrants are uncharged. If, however, the two pairs of quadrants are connected to sources at different potentials, the positively charged needle will be attracted by the negatively charged quadrants, and repelled by the positively charged quadrants, so that it will turn in the direction of the low potential pair. The deflexion will continue until the restoring couple due to the twist on the supporting wire, which is proportional to the deflexion, is sufficient to balance the electrical forces. The electrical forces can be shown to be proportional to the difference of potential between the opposite pairs of quadrants—that is, to the difference of potential between the two sources. The deflexion of the needle is thus proportional to the difference of potential between the sources, which can thus be measured. A mirror is usually attached to the needle to enable the deflexion to be measured with accuracy. The instrument can be made sufficiently sensitive to register a difference of potential of no more than $\frac{1}{300000}$th of the unit of potential which we have defined above.

300. Capacity.—*The potential of a given conductor is directly proportional to the quantity of electricity upon it*, just as the temperature of a given body is proportional to the amount of heat in it; but just as the capacity for heat is different for different bodies, so the capacity of different conductors for electricity is different for different conductors. It is quite easy to show experimentally that a charge which will raise a small sphere to a high potential will produce very little effect on the potential of a large one.

The electrical capacity of a conductor is the quantity of electricity which must be imparted to it to raise its potential by unity.

This may also be expressed by saying that *the capacity of a*

conductor is the ratio of the charge upon it to its potential. Thus, if Q is the charge on a conductor, and V its potential, then

$$C=\frac{Q}{V}, \text{ or } Q=CV$$

where C is a constant for the conductor, and is known as its **capacity.**

The electrical capacity of a conductor depends upon its size and shape, and can be calculated for certain simple cases. The capacity of a conducting sphere, when placed at a considerable distance from all other conductors, is numerically equal to its radius. Thus a sphere of 10 cms. radius will require 10 units of charge to raise its potential by unity.

301. Electrical Condensers.—The capacity of a conductor

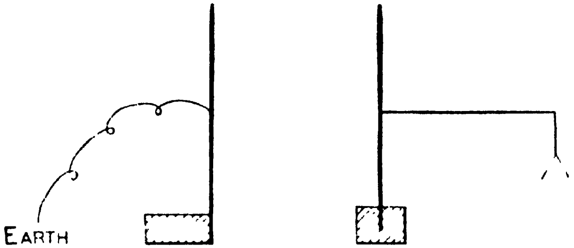


FIG. 240.—Parallel Plate Condenser.

depends not only on its own size and shape, but also on its position with respect to other conductors.

Any arrangement by which the electrical capacity of a conductor is increased is called an **electrical condenser.**

This increase in capacity is generally effected by placing an earth-connected conductor in close proximity to the insulated conductor.

The effect of the presence of an earth-connected conductor on the capacity of an insulated conductor can be studied conveniently with a pair of metal plates, one of which is insulated while the other is earthed. The plates are arranged facing each other, and the insulated plate is connected by a wire to the cap of a gold-leaf electroscope (Fig. 240).

(a) ***The capacity of the condenser is inversely proportional to the distance between the plates.***

While the plates are at some distance apart, the insulated plate is charged so that the leaves of the electroscope diverge widely. On moving the earthed plate nearer to the charged plate the leaves gradually fall together, showing that the potential of the plate is diminishing. On withdrawing the earthed plate to its original position the leaves again diverge, showing that the charge on the insulated plate has not been altered during the experiment. Since the charge has remained constant while the potential has diminished, the approach of the earthed plate must have increased the capacity of the insulated plate. Careful experiments show that the capacity is inversely proportional to the distance between the plates.

(b) *The capacity of the condenser is directly proportional to the specific inductive capacity of the medium between the plates.*

Keeping the plates at a fixed distance apart, charge the insulated plate as before, and introduce between the plates a thick slab of glass or other insulating material. The gold leaves fall together, showing that the capacity of the condenser is increased by the presence of the new medium. It can be shown that the capacity of a condenser is directly proportional to the specific inductive capacity (§ 289) of the medium between the plates. On this account *the specific inductive capacity of a medium is often defined as the ratio of the capacity of a condenser when the plates are separated by the given medium to the capacity of the same condenser when the plates are separated by air.*

(c) *The capacity of a condenser is proportional to the area of the insulated plate.*

A sheet of tinfoil, fastened like a blind to an insulated roller, is substituted for the insulated plate in the previous experiments. The tinfoil blind is unrolled and placed near the earthed plate to form a condenser. It is charged, and the divergence of the leaves of the electroscope is noted. The blind is gradually wound upon the roller, thus decreasing its exposed area, and at the same time the divergence of the leaves will be found to increase, showing that the potential is increasing. As the charge remains constant, the capacity of the condenser is therefore diminished by decreasing the area of the plate.

A pair of parallel plates, one of which is earthed, forms what is known as a **parallel plate condenser.** It can be shown that the capacity of a parallel plate condenser consist-

ing of two parallel plates each of area A and separated by a thickness d of some insulating medium of specific inductive capacity K is given by

$$C=\frac{KA}{4\pi d}$$

302. The Leyden Jar.—The Leyden jar is the form of condenser most often employed in electrostatic work. It consists of a wide-mouthed glass jar, the lower half of which is coated inside and out with a layer of tinfoil (Fig. 241). Contact with the inner coating is made by a brass rod passing through an insulating stopper and resting on the tinfoil. The upper portion of the glass jar is covered with shellac varnish to improve the insulation. The condenser thus consists of two conducting coats separated by a small thickness of glass. It may be regarded as a parallel plate condenser rolled up into the form of a cylinder.

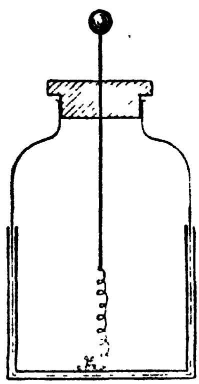


FIG. 241.—The Leyden Jar.

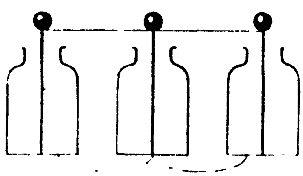


FIG. 242.—Leyden Jars arranged in parallel.

To charge it, the outer coat is earthed by holding it in the hand, and the brass knob is charged by being presented to one pole of an electrical machine or other source of supply. A considerable electrical charge can thus be stored in the jar, and if the two coatings are connected by a metallic rod a powerful spark may be obtained. Similarly, if the knob of the charged jar is touched while the outer coating is still held in the hand, a very disagreeable and, in the case of a large jar, a possibly dangerous shock will be felt.

For storing still greater quantities of electricity a number of these jars may be used; all the outer coatings being connected together, and similarly all the inner coatings (Fig. 242). The capacity of the resultant condenser is equal to the sum

of the capacities of the separate jars. The jars are said to be connected *in parallel.*

303. Principle of the Condenser.—Consider a charged sphere A at some distance from other conductors. The electric field will be uniform around it, and may be represented by a system of lines of force radiating out from the sphere as shown in Fig. 243. The potential of the sphere will be the work done against this field in bringing up a unit positive charge from the walls of the room to the sphere. Imagine a sphere B concentric with A, but of slightly larger

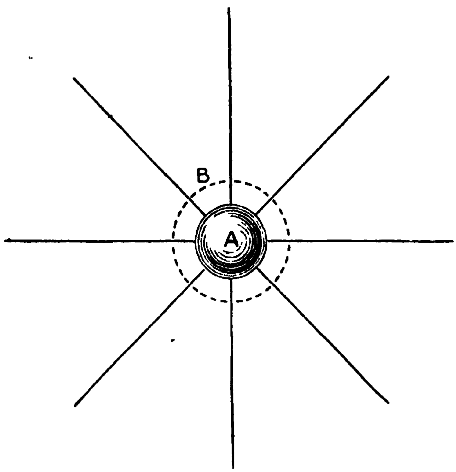


FIG. 243.—Diagram to illustrate the Principle of the Condenser.

radius. The potential of A is thus equal to the work done in bringing unit charge from the walls up to the surface B, plus the work done in moving the charge from B to the surface of A. If the distance between the two spheres is very small, the latter will be small compared with the former.

Now suppose the imaginary sphere B to be replaced by a conducting surface coinciding with it. This will divide the field of force into two parts, but will not otherwise affect the conditions. Now let us earth the sphere B. This will at once destroy the field between B and the walls of the room,

but since B is a closed conductor it will not affect the field between B and A, which therefore remains at its old value. But since we have destroyed the field between B and the walls of the room, no work will now be done against electrical forces in bringing a unit charge from the walls up to B. The potential of A, therefore, is now merely the work which must be done to move a unit charge from B to A. But, as we have seen, this is only a small fraction of the work which was originally required to bring a unit charge from the walls up to A before the sphere B was placed in position. Hence the potential of A has been decreased by surrounding it with the earthed conductor B. It is obvious that the nearer B is to A the smaller will be the potential of the latter. As the charge on A remains the same, its capacity is increased. This is the principle of the condenser.

304. Energy of a Charged Conductor.—By definition of potential, the work done in bringing a charge q up to the surface of a conductor at a potential V is equal to $q \cdot V$. Suppose we charge our conductor by bringing up to it successively a large number of small charges. As soon as the first charge is placed upon it the conductor will acquire a potential, and hence work will have to be done to bring up each of the successive charges to the surface of the conductor. The amount of this work will be proportional to the charge already on the conductor. It will be small at first when the potential is small, but will increase as the potential is raised by the presence of the charges already placed on the conductor. It can be shown that the work done in charging a condenser is the same as if the whole charge were placed upon it at its average potential during the charging process. Thus, if the conductor is originally uncharged, and its final potential is V, the average potential during the charge will be $\frac{1}{2}$V. If Q is the final charge upon the conductor, then the work done in charging the conductor is equal to the product of the whole charge into the average potential—that is, $\frac{1}{2}$QV ergs.

Since work has been done in charging the conductor, the conductor has *potential energy* equal to the work spent in charging it (§ 41). Thus—

The energy of a charged conductor $= \frac{1}{2}$QV ergs.

Since $Q = CV$, where C is the capacity of the conductor, we can write this relation in the form

$$E = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 \text{ ergs}$$

by substituting for Q; or by substituting for V we can write it in the form

$$E = \tfrac{1}{2}QV = \tfrac{1}{2}\frac{Q^2}{C} \text{ ergs}$$

This potential energy can be used for doing work, either electrical or mechanical. It is generally manifested in the form of an electric spark when the conductor is discharged. The electric spark from a highly charged condenser of large capacity is capable of producing considerable mechanical effects (for example, puncturing a glass plate), and is always attended with light, heat, and sound. All these phenomena are forms of energy.

EXAMPLES.

1. A conductor has a capacity of 100 units and is charged to a difference of potential of 20 units. Calculate (*a*) the charge on the conductor, (*b*) its electrical energy.
2. A parallel plate condenser has plates of area 300 square cms. and the distance apart of the plates is 3 millimetres. Calculate its capacity.
3. The plates of a parallel plate condenser are 1 mm. apart and are charged to a potential difference of 10 units. Without discharging the condenser the plates are separated to a distance of 1 cm. What is the potential difference?
4. A battery of four Leyden jars each of capacity 1000 units are connected in parallel and charged to a potential difference of 100 units. Calculate (*a*) the total charge on the jars, (*b*) the electrical energy of the system.
5. A Leyden jar of 500 units capacity is given a charge of 2000 units and is allowed to share this charge with another uncharged jar of equal capacity, by connecting the two in parallel. Assuming that no charge is lost in the process, calculate (*a*) the change in potential, (*b*) the change in electrical energy of the system, produced by connecting the jars.

CHAPTER VII

ELECTRICAL MACHINES

305. Production of Electrification.—Charges of electricity can be produced either by friction or by induction from another charge. In each case the production of a given quantity of positive electricity is attended by the simultaneous production of an equal quantity of negative electricity. The electrical charge, strictly speaking, is not produced, but only separated from the electrification of the opposite sign. A neutral body in reality contains immense quantities of both positive and negative electricity, but the amount of each being exactly the same, they exactly neutralise each other at all points. The quantity of electricity of each sign in a given body is not infinite, but it is immensely greater than the charges we are able to excite in our experiments. The total quantity of positive electricity contained in 1 cubic centimetre of water is about 15×10^{14}, or 150 million millions of our unit of electrical charge. This is infinitely greater than any charge we can excite in our experiments, so that for our purpo the supply may be regarded as inexhaustible.

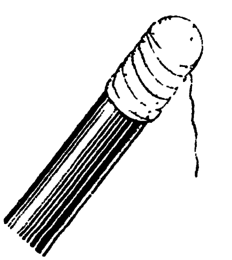


FIG. 244.—Experiment to show the Equality of the Charges produced by Friction.

The fact that the production of a given positive charge is always attended by the appearance of an equal negative charge has already been demonstrated in the case of inductive charges. It can be proved in the case of frictional electrification by simple experiments. For instance, make a flannel cap to fit a rod of ebonite, and fasten to it a silk cord (Fig. 244). The cap is placed on the end of the rod, and the silk is wound around it so that when the silk is pulled the cap revolves with

friction against the surface of the rod. Without touching the cap, bring the rod and cap together near the cap of an electroscope. There will be no effect on the leaves. Now lift off the cap by means of the silk thread, and test each of them separately. The rod is negatively charged, and the flannel cap positively charged. Since the two charges together have no effect on the electroscope, they must be equal and opposite.

306. Frictional Machines.—The production of electricity by friction can be made continuous by simple mechanical devices. For example, if a silk pad P (Fig. 245) is pressed against a glass cylinder C, and the latter is rotated on its axis, the friction of the glass against the pad will produce positive electricity on the glass, which can be collected by a series of sharp points A, placed nearly touching the glass. The point becomes strongly electrified negatively by induction from the positive charge on the glass, and discharges to the glass (§ 286), leaving the conductor positively charged. The effect is the same as if the positive charge on C was directly transferred to the conductor A. The working of the machine is improved if the rubber is smeared with an amalgam, and is earth-connected. Frictional machines have been displaced by machines working on the principle of induction, which give far more satisfactory results.

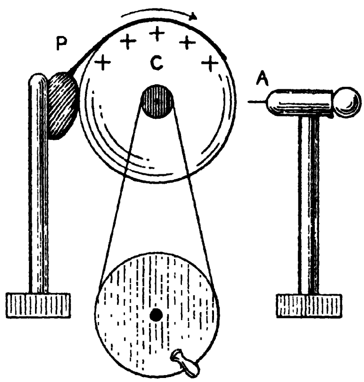


FIG. 245.—Frictional Machine.

307. The Electrophorus.—The electrophorus consists of a brass disk P (Fig. 246) known as the "plate," mounted on an insulating handle H. A somewhat larger circular disk C of ebonite, or a mixture of various waxes and resins, completes the apparatus. This "cake" is generally placed on an earthed metal dish S known as the "sole." The cake is given an initial charge by being rubbed with catskin or flannel. The metal plate is then placed on the cake, touched with the finger for a moment to earth it, and then lifted from the cake by

the insulating handle. The plate is charged positively by induction.

When the plate is placed on the cake, it makes actual electrical contact with it only at a very few points. Since the cake is an insulator its charge is not conducted to the plate. The negative charge on the cake, however, induces a positive charge on the lower side of the plate, and a negative charge on the upper, which passes to earth when the plate is touched by the finger. On removing the finger this charge is left insulated on the plate, and is removed with it when the

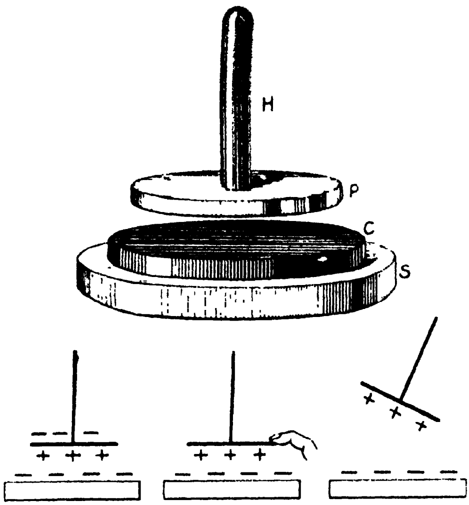


FIG. 246.—The Electrophorus, with diagrams to illustrate its action.

plate is lifted. As the original charge on the cake is not affected by the process, the operation can be repeated a large number of times until the original charge leaks away owing to imperfect insulation. Thus a very large number of positive charges can be obtained from a single negative charge.

As we have seen, a charged conductor possesses potential energy, and thus each of the charges carried away by the plate possesses a certain amount of energy. It would thus appear as if an indefinite amount of energy could be obtained from a single negative charge on the cake. This is not the case. The energy of the positive charges does not

come from the negative charge, but from the person who works the electrophorus. Since the positive charge on the plate and the negative charge on the cake attract each other, more work must be done to lift the plate from the cake when they are charged than when they are uncharged. It is

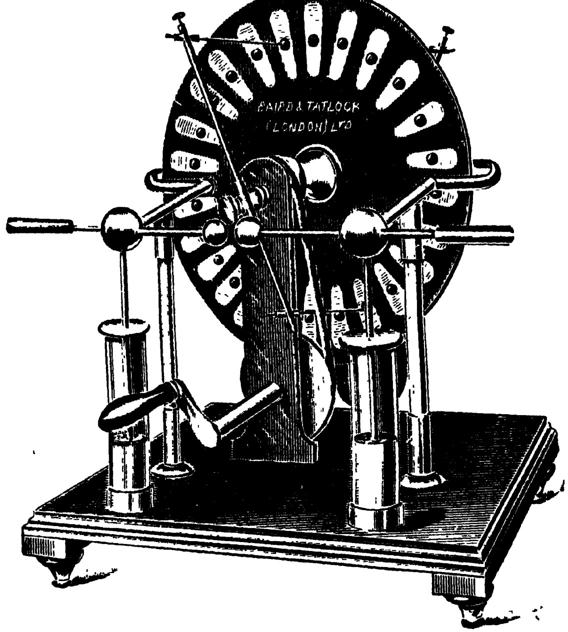


FIG. 247.—The Wimshurst Machine.

this excess of work that supplies the energy of the successive charges produced on the plate.

308. The Wimshurst Machine.—The usual method of producing a supply of electricity in the laboratory is the Wimshurst machine. The principle is that of the electrophorus, but the apparatus is designed so that the necessary succession of operations can be carried out mechanically and continuously by the turning of a handle.

The Wimshurst machine (Fig. 247) consists of two plates of glass or ebonite arranged to rotate in opposite directions by

turning a handle on the base of the instrument. The plates have a number of radial metallic sectors, the rest of the surface being made insulating by a coating of shellac varnish. At opposite ends of the horizontal diameter of the plates are placed collectors or combs, consisting of a number of sharp points projecting close to the rotating sectors on each side of the disks. They are connected with insulated metallic knobs, which form the poles of the machine. On each side of the machine two long rods make connection by means of metallic

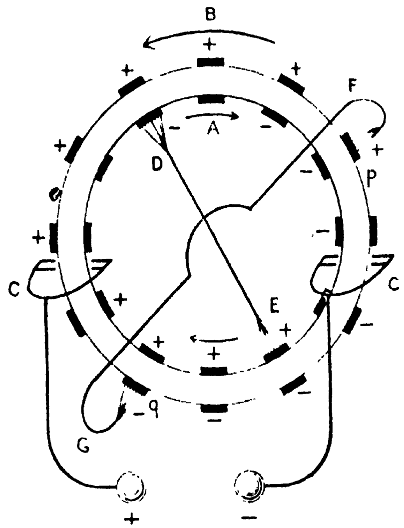


FIG. 247*a*.—Diagram to illustrate the Action of a Wimshurst.

brushes between opposite sectors of the plates. These brushes are set at right angles to each other, and making an angle of 45° with the line joining the combs. To work the machine a charged rod is held opposite one of the brushes and the handle turned. The conductors begin to charge up with electricity of opposite sign. The charged rod can then be taken away and the machine will continue to work indefinitely as long as the handle is turned. This will be shown by a succession of sparks between the poles of the machine.

The action of the Wimshurst will be understood from the diagram in Fig. 247*a*. A and B represent the two plates

rotating in the directions of the arrows, the metallic sectors being indicated by the dark lines. C, C′ are the two collectors or combs, while DE and FG represent the brushes.

Let us suppose that a negatively charged rod is held opposite F and the plates rotated. The brush F and the sector *p* in contact with it become positively charged by induction, a negative charge being repelled along the conductor to the brush G and the sector *q* touching it. These charged sectors are carried round by the revolving plates until they come opposite the ends D and E respectively of the other brush. Here they act inductively on this conductor so that the end D becomes negatively charged and the end E positively. These charges are carried off by the rotating sectors in the direction of the arrows, and come in turn opposite the ends of the brush FG, were they act inductively on the brushes, giving to the end F a positive charge and to the end G a negative. The charged rod can then be withdrawn, as the supply on the brush FG is now kept up by the action of the charged sectors coming from D and E. In the same way the charges on D and E are continually renewed by induction from the charged sectors coming from F and G. The machine once started will therefore continue to work.

After acting on the brushes the charged sectors are brought opposite the collectors C, C′, where they are discharged by the discharging action of the points, their charge passing through the collectors to the poles of the machine. It will be seen from the figure that both sets of sectors bring positive charges to the comb C, which thus becomes the positive pole of the machine, while negative charges are conveyed to the comb C′.

The energy of the charges produced comes from the work which must be done to move the oppositely charged sectors away from each other. Greater force must be applied to turn the plates when the machine is charged than in its uncharged condition, and this excess of work is transformed into the energy of the charges produced.

309. The Voltaic Cell.—Electricity can also be produced in other ways besides friction and induction. Of these the most important is the voltaic cell. If a plate of zinc and a plate of copper are dipped into a beaker containing dilute sulphuric acid, a difference of potential is set up between the two plates.

This difference of potential is so small that it will not sensibly affect the leaves of a gold-leaf electroscope. If, however, we take, say, 100 such cells and join the copper plate of one to the zinc plate of the next cell, and so on (Fig. 248), the difference of

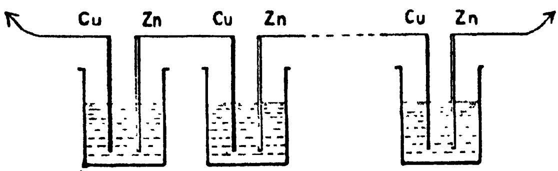


FIG. 248.—Voltaic Cells connected in Series.

potential between the copper plate at one end of the series and the zinc plate at the other will be sufficient to produce a measurable divergence of the leaves, when the one is connected to the leaves and the other to earth or to the case of the electroscope. It will be found that the wire coming from the copper is positive, that from the zinc is negative. The copper and the zinc plates therefore form the positive and negative poles of the cell.

The experiment can also be performed with a single cell by the use of a *condensing electroscope*. This consists (Fig. 249) of an ordinary electroscope in which the rod supporting the gold leaves terminates in a large flat circular brass disk covered with a thin layer of insulating shellac varnish. An exactly similar plate is laid upon the plate of the electroscope and is connected to earth. Since the plates are insulated from each other by varnish and the upper one is earthed, they form a condenser the capacity of which is large, since the plates are very close together. Connect the zinc plate to the upper brass plate, and the copper plate to the cap. Remove the wires and raise the upper plate from the lower. The gold leaves will be seen to diverge. It can easily be shown that the charge on the leaves is positive.

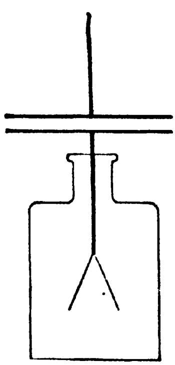


FIG. 249. —Condensing Electroscope.

The voltaic cell produced a difference of potential between the two plates of the condensing electroscope, too small to

cause an appreciable divergence of the leaves. Owing, however, to the great capacity of the system, the charge on the lower plate was appreciable in spite of its low potential. On raising the upper plate, the capacity of the lower plate was very greatly diminished. Since its charge remained the same, the potential rose correspondingly and was finally sufficiently great to cause a measurable divergence of the leaves.

We thus learn that *the potentials produced by the voltaic cell are very small compared with those produced by friction*, or by a Wimshurst machine. On the other hand, *a voltaic cell will produce in a given time far greater quantities of electricity* than a Wimshurst. For instance, if we join the poles of a Wimshurst machine by a very thin conducting wire, the electrical charges produced will flow along the wire from the positive to the negative pole, producing what is known as a **current of electricity**. The wire will not become appreciably warm. If, however, we join the poles of a voltaic cell by a similar piece of wire, the wire will become red-hot. Faraday, who first investigated the subject, found that a very small voltaic cell would produce in three seconds as much electricity as was produced by thirty turns of his largest electrical machine, the plate of which was 50 inches in diameter, and which was capable of giving an electric spark 14 inches in length.

Thus, if we wish to investigate the electrical forces between charges at rest, which depend mainly on the potential of the charges, we shall find our most convenient source of electricity in the Wimshurst. When, however, we come to investigate the effect produced by electricity in motion, where the magnitude of the effect depends largely on the quantity of electricity set in motion, we shall find it much more convenient to work with the voltaic cell. The part of the subject of electricity which we have already considered is known as **electrostatics**, since it deals with the effects produced by *charges at rest*. The study of the effects produced by *charges in motion*, that is, by *electric currents*, is known as **current electricity**.

EXAMINATION QUESTIONS.—XV

1. Describe experiments to show that when two unlike substances are rubbed together equal and opposite charges of electricity are produced.

2. State the law of force between two point charges, and describe an experiment to illustrate the law. Explain how the law is applied to define unit quantity of electricity.

3. Two insulated brass spheres, each of 2 cms. radius and situated 10 cms. apart, are charged with equal quantities of electricity. Illustrate by a diagram the distribution of electric force in the region between them when the spheres are charged with (*a*) the same, (*b*) opposite kinds of electricity. How would the force between them be altered if the spheres were immersed in paraffin oil of specific inductive capacity 2?

4. Describe experiments to illustrate electrostatic induction. In what circumstances is it possible to have a charge on the interior of a hollow conductor?

5. A positively charged body is brought near an uncharged insulated conductor. What will be the condition of the conductor as regards (*a*) charge, (*b*) potential? How could you test your statements with the aid of an electroscope?

6. Describe the mode of action of an electrophorus, giving diagrams to show the arrangement of the charges and the lines of force. What is the source of the energy produced?

7. How are induced charges of electricity obtained? Describe and explain the action of a Wimshurst machine.

8. What is meant by the capacity of an electrical conductor? How would you demonstrate the fact that the capacity of a conductor is altered by bringing into its neighbourhood another conductor?

9. Describe some form of electrical condenser. Explain what is meant by the capacity of a condenser, and point out the factors on which it depends.

10. Describe a condensing electroscope, and describe how by means of it a small potential difference, such as that between the poles of a battery of a few cells, may be shown.

11. Explain what is meant by the difference of potential between two points. What is meant by the statement that an electroscope indicates potential rather than quantity?

12. A charged metal rod and a charged ebonite rod are in

turn placed in contact with the knob of an electroscope. In each case the leaves diverge. When the metal rod is removed there is no change in the divergence, but when the ebonite rod is taken away the leaves partly collapse. Explain the difference.

13. Describe a gold-leaf electroscope, and show how it may be used to determine (*a*) the sign of the charge on an insulated conductor, (*b*) which of two small conductors has the greater charge.

14. A tall metal can is insulated and charged. How would you investigate the distribution of the charge over the surface of the can? What results would you expect to find?

15. Two small equal metal spheres are placed 5 cms. apart in air. What will be the force between them if one has a charge of $+5$ units and the other -10 units? The spheres are connected for a moment by a wire held by an insulated handle. What is the force now?

16. Explain the terms electric charge, electric potential. Under what circumstances can a negative charge be at a positive potential?

17. A positively charged conductor A is brought near (*a*) an insulated conductor B, (*b*) an earthed conductor C. What changes, if any, will be produced in the potentials of the three conductors, and what charges will be produced on B and C?

CHAPTER VIII

THE ELECTRIC CURRENT

310. The Electric Current.—If the two plates of a charged condenser are joined by a conducting wire, the positive electricity flows along the wire from the high to the low potential plate until the two are at the same potential. There is thus a passage of electricity along the wire which may be compared to the flow of water along a pipe from a higher to a lower level. We therefore say that during the discharge there is a *current of electricity* or an *electric current* flowing along the wire. In the case of the discharge of a condenser the flow is only momentary. If, however, we connect the two poles of a Wimshurst while it is working by a conducting thread, there will be a continuous flow of electricity along the thread from the high to the low potential pole. We thus get a continuous current. As we have seen, a voltaic cell will produce in a given time a much greater quantity of electricity than the largest electrical machine, so that if the poles of a voltaic cell are joined by a conducting wire a large and continuous current of electricity flows along the wire.

The simple form of voltaic cell already described (§ 309) is not very satisfactory, as owing to the deposition of gas on the plates its action rapidly weakens. Improved forms of the voltaic cell have, however, been devised which overcome this difficulty, and are capable of supplying considerable currents for an almost indefinitely long time. The most useful of these *cells*, or *batteries* as they are often called, are the *Daniell*, the *Bichromate*, and the *Leclanché*. These are described in a later chapter (§ 337 *et seq.*).

311. Effects produced by the Electric Current.—When a current is flowing along a conductor various effects are produced in and around it.

(*a*) Magnetic Effects.—If the wire carrying the current is placed parallel to the magnetic axis of a compass needle

the needle will be deflected, and will tend to set itself at right angles to the direction of the current. Thus an electric current produces a magnetic field.

(*b*) THERMAL EFFECTS.—Heat is produced in the wire by the passage of the current. If the current is strong and the wire thin, the heat produced may be sufficient to raise the wire to incandescence, as in the case of the metallic filaments in electric flash lamps.

(*c*) CHEMICAL EFFECTS.—If the wire carrying the current is cut, and the ends are dipped into acidulated water, bubbles of gas are seen coming off from each of the cut ends. These gases can be shown to be hydrogen and oxygen. Thus the water is decomposed into its elements by the action of the current.

We shall have to consider each of these effects in turn.

312. Direction of the Current.—The current is regarded as flowing from the positive to the negative pole of the cell —that is, from the copper to the zinc. We thus agree to consider only the motion of the positive electricity and to neglect that of the negative electricity, which, of course, will flow from the negative to the positive pole. Thus if a positively charged conductor A is connected to a negatively charged one B, we agree to regard the resulting action as a flow of positive electricity from A to B. We might equally well have expressed the result by saying that negative electricity flows from B to A. A current of positive electricity from A to B is experimentally indistinguishable from a current of negative electricity from B to A. As a matter of fact, we now know that it is the negative electricity which moves through the conductor, the positive remaining at rest. It is, however, too late to alter the nomenclature of the subject, so that *when we speak of the direction of a current we mean the direction in which the positive electricity is supposed to flow.*

313. Magnetic Field due to a Current.—If a straight wire carrying a current is placed parallel to the axis of a suspended magnetised needle the needle will be deflected and will tend to set at right angles to the current. If the wire is above the needle and the current is running from south to north, the north pole will be deflected to the west; if the wire is placed below the needle the north pole will turn towards the east. If the direction of the current is reversed, so that it flows from north to south, the direction of the deflexion will also be reversed.

There is thus a definite relation between the direction of the current and the magnetic field which it produces.

The lines of magnetic force due to a current flowing in a straight wire are a system of concentric circles with their centre in the wire. This can be deduced from the experiments with the compass needle which we have just been considering. It can also be shown directly by passing a vertical wire bearing a current through a small hole in the centre of a horizontal sheet of cardboard so that the wire is at right angles to the cardboard. If iron filings are sprinkled over the sheet, they will set themselves in the form of a series of circles around the wire, as shown in Fig. 250.

The direction of these lines of force, that is the direction in which a north pole would be urged, bears a definite relation to the direction of the current. There are various devices for remembering this relation. One of the simplest is to suppose that we are screwing a corkscrew into a cork in the direction in which the current is travelling. The direction in which a north pole would be urged round the current is the direction in which the thumb travels round with the corkscrew (Fig. 251). In other words, *the direction of the lines of the magnetic field due to a current bears the same relation to the direction of the current as the rotation bears to the translation in a right-handed screw.* The student should apply this rule to the deflexion of a magnetic needle already described.

314. The Galvanoscope.—If the straight wire carrying the current is bent so as to return beneath the needle as shown in Fig. 252, then it can be seen by the application of our rule that in the space between the wires the field produced by the portion of the current flowing above the needle is in the same direction as the field produced by the portion of the current below the needle. The force on the needle will, therefore, be doubled, and the deflexion correspondingly increased. Similarly, if instead of a single turn around the needle we loop our wire several times round the needle, each turn of wire will produce its own additional force, and the deflexion will become still greater.

An instrument of this kind forms a very sensitive detector of current, and is known as a **galvanoscope.** It must, of course, be set so that the plane of the coils of wire is parallel to the magnetic needle—that is, in the magnetic meridian.

315. The Electric Telegraph.—If a galvanoscope is con-

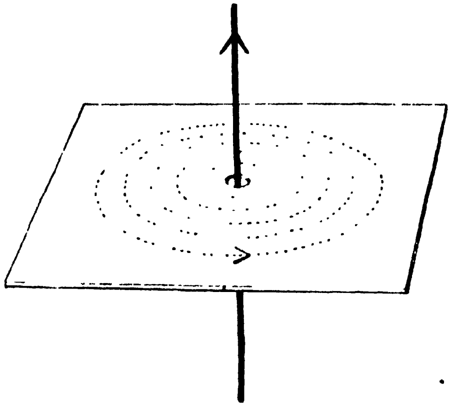


FIG 250.—Lines of Magnetic Force due to a Straight Current.

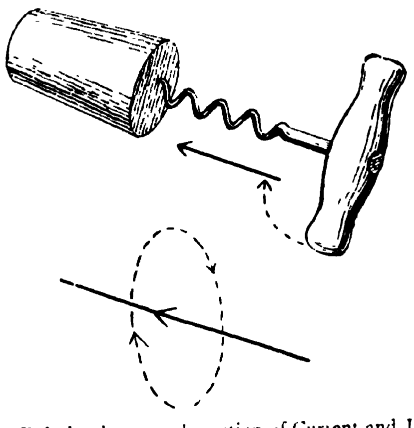


FIG 251.—Relation between Direction of Current and Direction of Lines of Force.

FIG. 252.—Principle of the Galvanoscope.

nected in series with a battery and a key, on completing the circuit by pressing the key a current will flow, and the needle of the instrument will be deflected. If the circuit is broken, the needle will return to its normal position. If the current is reversed, by reversing the connections with the battery the needle will be deflected in the opposite direction. In this way a series of signals can be transmitted from the key to the galvanoscope. These signals can be arranged into an alphabetical code by which messages can be transmitted. The reversal of the current in the circuit can be effected by a special key, known as a commutator or reversing key. The whole arrangement is a simple form of electric telegraph. The distance apart of the battery and key, or transmitting station, and the galvanoscope, or receiving station, may be very great, providing that the battery is sufficiently strong to produce an appreciable current through the conducting wires joining the stations.

316. Strength of Magnetic Field produced by a Current. – The strength of the magnetic field at a given point due to a current will depend in the first place on the strength of the current. The greater the current the greater the effect which it will produce. It will also depend on the distance of the point from the current. The closer we bring our current-bearing wire to the magnetic needle the greater the deflexion.

To investigate the variation of the field with the distance we must arrange the wire carrying the current so that each part of it is at the same distance from the point where the field is to be measured. If not, the results will be complicated by the fact that different portions of the current are at different distances from the point of observation. We can do this by bending the wire carrying the current into the form of an arc of a circle having the given point for its centre.

It is found by experiment that if a wire of length l carrying a constant current is bent into the arc of a circle of radius r, the magnetic force at the centre of the circle is *inversely proportional to the square of the radius*—that is, of the distance of the point from the current.

If we keep the radius fixed and increase or decrease the length of the wire carrying the current, the magnetic field at the centre is *directly proportional to the length of the wire.*

Thus if a wire of length l carrying a current C is bent into

the arc of a circle of radius r, the magnetic field F at the centre of the circle due to the current is given by

$$F \propto \frac{l \cdot C}{r^2}$$

This result is used to define a unit of current.

Unit current is defined as that current which, flowing in a wire of unit length bent into the arc of a circle of unit radius, will produce at the centre of the circle a magnetic field of unit intensity (1 gauss).

As the current is measured by the magnetic effect which it produces, the unit of current as defined above is known as the **electro-magnetic unit of current.** All electrical measurements are made in C.G.S. units. When the current is measured in this electro magnetic unit just defined we have, from the definition

$$F = \frac{l \cdot C}{r^2}$$

317. The Tangent Galvanometer.—Suppose we have n turns of wire wound in a circular groove of radius r. Then, since each portion of the wire will be at the same distance from the centre of the circle, the magnetic field F at the centre due to a current C flowing in the wire will by the previous equation be given by

$$F = \frac{(\text{total length of wire}) \times C}{r^2}$$

Since there are n circles of wire each of radius r, the total length of wire is $2\pi r \cdot n$. Hence, substituting this value, we have

$$F = \frac{2\pi r n C}{r^2} = \frac{2\pi n C}{r}$$

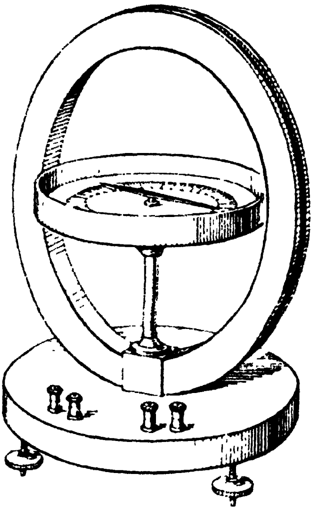
where C is measured in the absolute electro-magnetic unit just defined.

This result affords us a convenient practical method of measuring currents. Our rule for determining the direction of the field shows that the field F is at right angles to the plane of the circle on which the wire is wound. If we set the plane of the coils parallel to the magnetic meridian, the field due to the current will be at right angles to the magnetic field of the earth. A small compass needle suspended at the

centre of the coils (Fig. 253) will thus be acted upon by two fields at right angles to each other. The deflexion θ produced when the current passes is therefore given (§ 269) by

$$F = H \tan \theta$$

where H is the horizontal component of the earth's magnetic



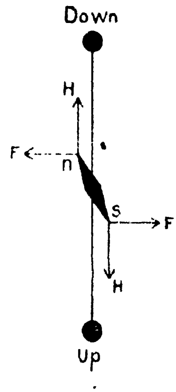


FIG. 253 -The Tangent Galvanometer.

field. Substituting for F from the previous equation we have

$$\frac{2\pi n C}{r} = H \tan \theta$$

$$C = \frac{Hr}{2\pi n} \tan \theta$$

This equation enables us to determine C if the deflexion θ is measured.

The instrument used for this purpose is the **tangent galvanometer**. It consists (Fig. 253) of a vertical circular frame wound with a number of turns of insulated wire, the ends of which are for convenience brought to terminals on the base of the instrument. At the centre of the circle is suspended a small magnetic needle which is free to turn in a

horizontal plane. The needle carries a long aluminium pointer the ends of which move over a circular horizontal scale graduated in degrees. The deflexions of the needle are read on the graduated scale.

To use the galvanometer the plane of the coils is set in the magnetic meridian (parallel to the magnetic needle), and the reading of the ends of the pointer is taken. The current to be measured is passed through the coils, the needle is deflected, and the new reading of the ends of the pointer again noted. The difference between the two readings measures the deflexion produced by the current. To avoid errors which might be produced by the coils not being exactly in the meridian, the direction in which the current flows through the coils is reversed so that the needle deflects to the opposite side of the scale. The mean of two values so obtained is taken as the true deflexion θ.

The current C is then given by

$$C = \frac{Hr}{2\pi n} \tan\theta$$

(*Note.*—The coils must be set *parallel* to the magnetic *needle*. If they are set at right angles to the meridian, that is, parallel to the pointer, there will be no deflexion at all, since the field due to the current which acts at right angles to the coils will now be acting in the same line as the field of the earth.)

Since the value of H differs in different places, the same current will produce different deflexions in the galvanometer at different places. The fraction $\frac{2\pi n}{r}$, on the other hand, depends only on the construction of the instrument and is a constant for a given galvanometer. It is known as the **galvanometer constant.** If we denote it by G, then

$$C = \frac{H}{G} \tan\theta$$

318. Practical Unit of Current.—The unit of current as defined above is known as the **absolute electro-magnetic unit,** since it is based directly on the C.G.S. system of units. It was found somewhat too large for practical purposes, and a current of exactly one-tenth of the absolute unit is employed in practical measurements. This current is known as the

The factor by which the tangent of the deflexion must be multiplied to give the current in amperes is known as the **reduction factor** *of the galvanometer.* Thus, if K is the reduction factor of a given galvanometer, we have

$$C \text{ (in amperes)} = K \tan \theta$$

By comparison with the previous equation we see that for a tangent galvanometer $K = \frac{10Hr}{2\pi n}$. Its value therefore depends on the place where the instrument is used.

319. Quantity of Electricity conveyed by a Current.— If we regard the electric current as a current of electricity flowing through the conductor, and therefore as analogous to a current of water flowing through a pipe, the current can be measured by finding the quantity of electricity passing any given point on the conductor in a unit of time. In the case of the flow of water the current is measured by the number of litres or gallons passing a given point in 1 second. Similarly, the electric current can be measured by the number of units of electricity passing a given point in 1 second. A current will be said to be of unit strength if 1 unit of charge passes any point in the circuit in 1 second. Thus, if Q is the charge passing any given point on the conductor in a time t, the current C in the conductor is measured by

$$C = \frac{Q}{t}$$

Hence $$Q = C \, . \, t$$

The quantity of electricity passing a given point on a conductor conveying a current C *in a time* t *is equal to* C . t, *the product of the current into the time for which it flows.*

The quantity of electricity conveyed by a current of 1 *ampere flowing for* 1 *second is the practical electro-magnetic unit of electric charge. It is known as the* **coulomb.**

This unit of quantity is very much larger than the one employed in electrostatics, and defined in § 288. It is found by experiment that a current of 1 ampere conveys 3×10^9 electrostatic units of charge past any point in the circuit in 1 second. That is to say, one coulomb $= 3 \times 10^9$ electrostatic units of charge. The coulomb is always used as the unit of quantity in experiments on current electricity.

320. The Thomson Galvanometer.—The sensitiveness of a galvanometer—that is to say, the deflexion produced by a given current—can be increased

(*a*) By increasing the number of turns of wire on the instrument.

(*b*) By decreasing the radius of the turns, and so bringing them nearer to the magnetic needle.

(*c*) By decreasing the magnitude of the earth's field at the centre of the coils. This can be effected by arranging a permanent bar magnet so that the field produced by it at the centre of the coils is very nearly equal and in the opposite direction to that of the earth. The resultant field on the needle due to the fixed magnet and the earth is thus very much smaller than that due to the earth alone.

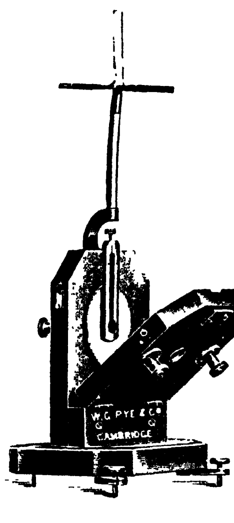


FIG. 254.—Thomson Galvanometer.

These modifications are embodied in the Thomson galvanometer, shown in Fig. 254. It consists of a very large number of turns of insulated wire wound on a circular frame of comparatively small radius. A bar magnet is placed above the coils, and can be adjusted so as to reduce the resultant field at the centre of the coils to a very small value.

The suspended magnet consists of a small piece of magnetised watch-spring, and is attached to a mirror. A beam of light is passed through a narrow slit and falling on the mirror is reflected from it to a graduated scale. This beam of light serves the purpose of a pointer. It can be shown from the laws of reflexion of light that if the mirror

is deflected through an angle θ, the beam of light will be deflected through twice this angle. If the distance between the mirror and the scale is large, a very small deflexion of the mirror will cause a large movement of the spot of light produced by the beam on the scale. Thus, if the distance of the scale from the mirror is 1 metre, a deflexion of the mirror of 1° will cause a movement in the spot of light of 3½ cms. As a movement of 1 mm. can easily be seen, it is obvious that a much smaller deflexion can be measured by this method than by means of an aluminium pointer attached to the needle. This device is usually adopted when a small deflexion has to be measured.

321. The Astatic Galvanometer.—Two magnetised needles of the same size and strength are mounted parallel to each other on the same support with their north poles pointing in opposite directions, and the system is suspended by a piece of unspun silk. If the two needles were exactly of the same strength, the couples produced by the earth's magnetic field would be the same for each needle, but would act in opposite directions, so that there would be no resultant couple upon the system as a whole. Such a system is known as an **astatic combination.** It is impossible to magnetise the needles to exactly the same strength. Thus the system will generally have a feeble tendency to set in one particular direction, but it will be very small. If now a coil of wire is wound round the two needles in the way shown in the figure (Fig. 255), it will be seen that a current flowing through the coils will tend to deflect each of the needles in the same direction. As the resultant couple due to the earth is very small, a very small current will suffice to produce a very appreciable deflexion. The instrument is known as an astatic galvanometer. It is only used as a detector of currents.

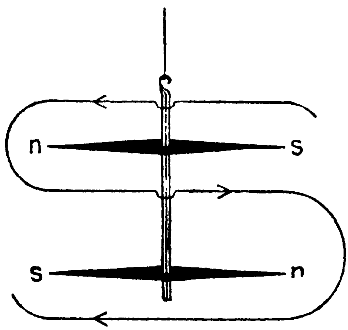


FIG. 255.—Principle of the Astatic Galvanometer.

The principle of the astatic galvanometer can of course also be applied to reflecting galvanometers of the Thomson type.

EXAMPLES.

1. Calculate the magnetic fields produced at the centre of a coil of wire consisting of 20 turns each of radius 10 cms. when conveying a current of (*a*) 2 absolute electro-magnetic units, (*b*) 3 amperes.

2. A tangent galvanometer has 200 turns of wire each of radius 8 cms. Calculate its reduction factor, for a place where $H = 0{\cdot}18$ gauss.

3. What will be the current through the coils of the galvanometer in Question 2 when the deflexion is 30°?

4. What current would be required to produce the same deflexion in the instrument if it was taken to a place where the value of H is 0·32 gauss?

5. A voltaic cell furnishes a current of 2 amperes for 20 minutes. Calculate the quantity of electricity generated by the cell in this time.

6. A circular coil of wire of radius 6 cms. and containing 30 turns of wire is placed with its plane at right angles to the magnetic meridian, and it is found on plotting the field that there is a neutral point at the centre of the coil. Calculate the current passing round the coil, the value of H being 0·18 gauss.

CHAPTER IX

ELECTRO-MAGNETISM

322. Lines of Force in the Field of a Circular Current.—The lines of force in the field produced by a current flowing in a circle can be plotted with a small compass needle in exactly the same way as any other field of magnetic force (§ 264). The vertical coils of a tangent galvanometer from which the needle has been taken away can be used, and two drawing-boards supported one on each side of the coil so that their

FIG. 256 (*a*).—Magnetic Field due to a Circular Coil of Wire carrying a Current.

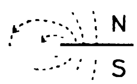


FIG. 256 (*b*).—Magnetic Field due to a Magnetic Shell.

plane contains the horizontal diameter of the coil. The field thus plotted will of course be the resultant of the field due to the current and that of the earth, and will depend on the direction made by the coil with the meridian. The student should plot these fields for himself for different positions of the coil.

The field due to the coil alone is shown in Fig. 256*a*. The lines of force are closed curves surrounding the current. This field of force is similar to that produced by a thin plate of iron or steel magnetised so that its axis is at right angles to the surface of the plate—that is, so that one face is a north pole and the other a south (Fig. 256*b*). Such a sheet is known as a **magnetic shell.**

A current flowing in any closed circuit acts exactly like a magnetic shell, the edges of which coincide with the wire carrying the current, and the behaviour of the one can be deduced from that of the other. This is known as **Ampère's law.**

Thus our circular coil of wire when carrying a current behaves as if one face of it were a large north pole, and the opposite face a south pole. Thus, if the north pole of a magnet is brought near one side of the coil, the latter will be attracted; if near the other, it will be repelled. Again, if the coil is free to turn, it will set itself in a magnetic field in exactly the same way as a compass needle. It must be remembered that as the magnetic axis of the coil is at right angles to the plane of the coil, the latter will set at right angles to the field.

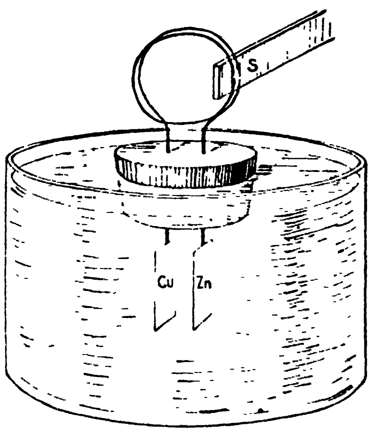


FIG. 257.—De la Rive's Floating Battery.

These results can be illustrated very simply by the floating battery of **de la Rive.** A copper and a zinc plate are floated in dilute sulphuric acid by means of a large cork, and the plates are connected by a small circular coil of several turns of wire. A current passes from the copper to the zinc, as shown in Fig. 257. If the north pole of a bar magnet is presented to the side nearest the spectator in the figure, the coil will move towards the pole; if to the other side, the coil will be repelled. If left to itself, the coil will set so that its plane is at right angles to the meridian—that is, with its magnetic axis in the meridian.

323. Moving Coil Galvanometers.—The couple on a coil suspended in a magnetic field is, under given circumstances, directly proportional to the strength of the current passing through the coil; the effect can thus be used for measuring currents. A coil of several turns of thin insulated wire is suspended by a phosphor bronze suspension between the

poles NS of a strong permanent magnet (Fig. 258). A cylinder B of soft iron is placed within the coil (without touching it) to concentrate the lines of force of the magnet upon the coil. The current enters the coil through the suspension and leaves by a very flexible spring.

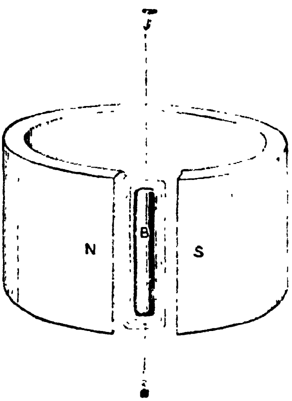


FIG. 258.—Moving Coil Galvanometer.

When no current is flowing, the plane of the coils is set in the plane of the magnetic field, *i.e.* parallel to the lines of force. When the current passes, there is a couple tending to set the coil at right angles to the field. This is resisted by the torsion of the suspension, and the coil assumes some intermediate position. It can be shown that the deflexion of the coil is directly proportional to the strength of the current in the moving coil. This property is very convenient in instruments designed to give the strength of a current directly by the motion of a pointer over a graduated scale, and most **ammeters**, as these instruments are called, work on this principle.

Another advantage of this type of galvanometer is that it is not affected by small external magnetic fields, as is the case with instruments like the Tangent, or the Thomson galvanometer, in which a suspended magnet is employed.

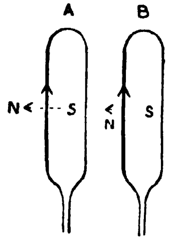


FIG. 259.—Attraction between two Currents.

324. Magnetic Attraction of Two Currents.—Since a current flowing in a circuit is equivalent to a magnetic shell, two currents flowing in neighbouring circuits will behave towards each other like two magnets. Thus, if two coils are placed close together with their planes parallel, they will either attract or repel each other according to the direction in which the currents are flowing. The polarity of the faces can be determined by the corkscrew rule (§ 313). It will be found that if the current is flowing in the same direction in each

coil, the adjacent faces of the two coils will be of opposite polarity, and there will be attraction (Fig. 259); if the currents are flowing round the coils in opposite directions, the adjacent faces will have the same polarity, and there will be repulsion.

325. **Electro-Magnets.**—If we wind wire (covered with insulating material such as cotton or silk) upon a long cylinder, starting at one end and winding the wire always in the same direction until the other end is reached, we have what is known as a **solenoid** (Fig. 260). If a current is passed through the solenoid, each of the separate turns of wire acts as a magnetic shell with its axis parallel to the axis of the cylinder. There is thus a magnetic field inside the solenoid the lines of which are parallel to the length of the cylinder. One end of the solenoid will therefore behave as a north pole, the other as a south. The polarity can be determined from the direction of the current by the

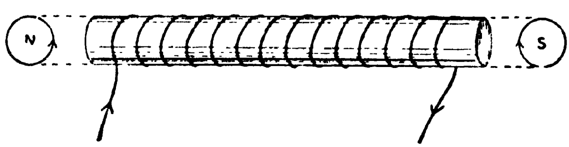


FIG. 260.—Magnetic Field due to a Solenoid.

corkscrew rule. If the current is flowing in the direction indicated by the arrows, the polarity will be as shown in the figure.

The field inside a long solenoid is very nearly uniform. It can be shown that the field F inside a long solenoid is given by

$$F = 4\pi nC$$

where n is the number of turns of wire on unit length of the cylinder, and C is the current measured in absolute electro-magnetic units. Thus, if the solenoid has 10 turns to the centimetre, and a current of 1 ampere, that is, $\frac{1}{10}$th absolute unit, is passed through the coils, the magnetic field inside the solenoid will be $4\pi \times 10 \times \frac{1}{10}$, that is, 12·5 gauss. It is evident that if large currents are available very strong magnetic fields can be produced in this way.

If a bar of iron or steel is placed in the solenoid it will become magnetised by the field. If steel is used the

magnetism will persist after the current is cut off. This is the best way of making permanent magnets. If the solenoid is wound on a soft iron core the iron will become a strong magnet while the current is passing, but will lose its magnetism when *the current is cut off.* It forms what is known as an **electro - magnet.** Electro-magnets are generally made in the form shown in Fig. 261. The cylindrical iron cores are firmly bolted down on a soft iron base, each core being furnished with its own magnetising coil. If the magnet is to be one of the usual type, having a north and south pole, the coils must be arranged so that the current flows round them in opposite directions as seen by an observer looking down upon the magnet from above, as indicated by the small circles placed above the poles in the figure. If the direction of the current through the magnet is reversed, the polarity will also be reversed.

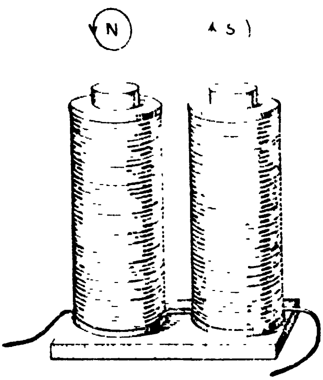


FIG. 261.—Electro-Magnet.

EXAMINATION QUESTIONS.—XVI

1. What are the principal effects of an electric current? What experiments would you make to demonstrate them?

2. Describe experiments to show the way in which a magnetic field is associated with an electric current. Under what circumstances can the measurement of a magnetic field serve as a measure of the electric current?

3. Explain how the strength of a current is defined. Describe fully one method of measuring the strength of a current.

4. Sketch the lines of magnetic force due to an electric current flowing round a circular coil, neglecting the earth's magnetic field. Explain the method of measuring the strength of a current by observations on the deflexion of a magnetic needle suspended at the centre of the coil.

5. Describe the construction and method of use of a tangent galvanometer.

6. What is meant by the reduction factor of a galvanometer? A tangent galvanometer has 20 coils, each of 8 cms. radius. Calculate the reduction factor of the instrument for a place where $H = 0{\cdot}20$.

7. A current flowing through a tangent galvanometer consisting of 10 turns of wire, of radius 8 cms., produces a deflexion of $45°$ when the instrument is in a place where $H = 0{\cdot}18$ dyne per unit pole (gauss). What is the current? What alterations would you make in the instrument so that it would give the same deflexion for a current of $\frac{1}{1000}$th of an ampere?

8. Describe some form of sensitive galvanometer, explaining the principle on which its action is based.

9. Describe experiments to show that a circuit carrying a current behaves like a magnet. Under what circumstances will two neighbouring circuits repel each other?

10. Describe some form of moving coil galvanometer, and explain the principle on which it acts. What are the advantages of this form of galvanometer?

CHAPTER X

ELECTROLYSIS

326. Two Kinds of Conduction.—If the poles of a voltaic cell are joined by a metallic wire, a current passes. The wire is a conductor of electricity. If the wire is cut and the ends dipped into a solution of dilute sulphuric acid in water, the current continues to flow. The solution is also a conductor. The mechanism of the conduction is, however, very different in the two cases. In the case of the wire there is no motion of the molecules of the wire. This can be verified by pressing a rod of silver against the end of a rod of copper, and passing a current across the junction for some time. If the rods are then separated and chemically analysed, it is found that there is no trace of silver in the copper, and no copper in the silver. The current has passed from one to the other without any transference of the material of the bars.

On the other hand, when the current is passing through the dilute sulphuric acid, it is obvious that the substances in the solution are affected by the current. A stream of bubbles can be seen coming off at each of the wires dipping into the solution, showing that the solution is being decomposed by the passage of the current. This type of conduction is called *electrolytic*, and the liquid is called an **electrolyte.**

327. Electrolytes.—*A substance in which the passage of an electric current is attended with chemical decomposition is known as an electrolyte.*

The most common electrolytes are solutions of salts, acids, and bases in water. Many fused salts also act as electrolytes—such, for example, as fused potassium hydroxide. A few solid electrolytes are also known, for example silver iodide.

The conductors by which the current enters and leaves the electrolyte are known as **electrodes**; the positive electrode is called the **anode,** the negative one the **cathode.** A vessel

fitted with electrodes and containing an electrolyte is known as an electrolytic cell.

328. Electrolysis.—Suppose we take an electrolytic cell containing dilute sulphuric acid, and invert burettes over the electrodes to collect and measure the gases evolved. If we pass a constant current through the cell it can quite readily be seen that the gas is evolved at a constant rate; the total amount of gas evolved is therefore directly proportional to the time for which the current has been flowing. Again, if we increase the current, the rate of evolution of gas is also increased; if we diminish it, the rate of evolution of gas is also diminished. Thus the quantity of gas evolved is also directly proportional to the strength of the current.

The gas evolved at the anode will be found to be oxygen, and that at the cathode hydrogen, and it will readily be seen

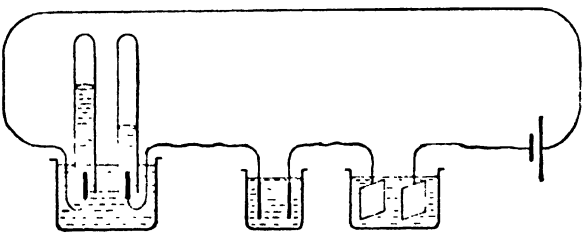


FIG. 262.—Experiment to verify Faraday's Laws of Electrolysis.

that the volume of the hydrogen is exactly twice that of the oxygen. But we know that one volume of oxygen is chemically equivalent to two volumes of hydrogen. Thus the masses of the two substances evolved are directly proportional to their chemical equivalents. This is a particular instance of a general law. Let us arrange a number of electrolytic cells in series (Fig. 262), say, one containing dilute sulphuric acid as before, one a solution of silver nitrate, another containing a solution of copper sulphate, and so on. We may also make the cells of different sizes, some with electrodes of thin wire, and others in which they consist of large plates immersed in the solution. The same current is now passed through the whole of the cells for some convenient time, and the products of electrolysis are collected and weighed. Hydrogen and oxygen are liberated at the poles of the cell containing the acid, silver is deposited on the cathode of the cells containing

silver nitrate, and copper on the cathode of the copper sulphate cells. It will be found

(*a*) *That the same weight of any given element is deposited in each of the cells in which it is one of the products of decomposition*—that is to say, the amount of copper deposited is the same; whether the cell is large or small, whether the electrodes are close together or far apart, and whether the electrolyte consists of, say, copper sulphate or copper nitrate.

(*b*) The weights of the different elements deposited are directly proportional to their chemical equivalents. Thus, if the amount of hydrogen evolved weighs 1 gram, the weight of the oxygen liberated will be 8 grams, that of the copper 31·5 grams, and silver 108 grams.

329. Faraday's Laws of Electrolysis.—These results, which were first obtained by Faraday, may be summarised in the following laws:

I. The mass of any substance liberated from an electrolyte by the passage of a current is directly proportional to the strength of the current and to the time for which it flows.

II. If the same current passes for the same time through different electrolytes, the masses of the different substances liberated will be directly proportional to their chemical equivalents.

Since the product of the strength of the current into the time for which it flows measures the total quantity of electricity passing through the apparatus, the first law may be stated in the form—

The mass of any substance liberated from an electrolyte is directly proportional to the quantity of electricity which has passed through it.

The mass of a substance deposited by the passage of unit quantity of electricity is known as the **electro-chemical equivalent** *of the substance.*

It is generally measured by the *weight in grams deposited during the passage of* 1 *coulomb.* Thus, if e is the electro-chemical equivalent of copper, the weight of copper deposited by the passage of q units of electricity will be given by

$$m = eq$$

If the decomposition is effected by a constant current of strength c (amperes) passing for a time t (seconds), we have from the above

$$m = ect$$

If we measure the current passing through an electrolytic cell, the time for which it flows, and the mass of the substance deposited, its electro-chemical equivalent can be determined from the relation

$$e = \frac{m}{ct}$$

It follows from the second law that the *electro-chemical equivalents of the various substances are directly proportional to their chemical equivalents.* Thus, if we know the electro-chemical equivalent of one element, those of the others can be calculated from their chemical equivalents. The electro-chemical equivalent of silver has been determined with the greatest accuracy. It is found that a current of 1 ampere flowing for 1 second deposits 0·001118 gram of silver from a solution of a silver salt. The electro-chemical equivalent of silver is therefore 0·001118 gram per coulomb. Since its chemical equivalent is 108, the electro-chemical equivalent of hydrogen is $\frac{0·001118}{108}$, that is, 0·00001038. That of any other substance can be obtained by multiplying the electro-chemical equivalent of hydrogen by the chemical equivalent of the substance.

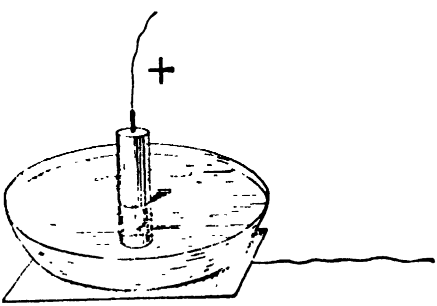


FIG. 263.—Silver Voltameter.

330. Voltameters.—These results afford a method of measuring the quantity of electricity passing through a given circuit. An electrolytic cell is connected in series in the circuit, and the mass m of substance deposited on one of the electrodes is measured. If e is the electro-chemical equivalent of this substance, then the quantity of electricity which has passed through the circuit is given by

$$q = \frac{m}{e}$$

An electrolytic cell used for this purpose is called a

voltameter. The silver voltameter is the most accurate. It consists of a platinum dish (Fig. 263) containing a solution of silver nitrate in water, which forms the cathode, while a silver rod dipping into the solution is the anode. Silver is deposited on the dish, and its weight can be determined by weighing the dish before and after the experiment. For laboratory purposes a copper voltameter is often used in which copper sulphate is substituted for the more expensive silver nitrate, and both the electrodes are of copper. The copper is deposited on the cathode or negative electrode. The defect of the copper voltameter is the ease with which the deposit of copper becomes oxidised during the processes of drying and weighing.

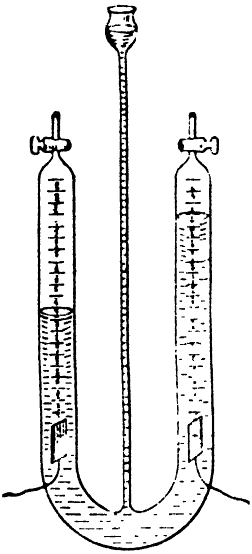


FIG. 264.—Hydrogen Voltameter.

A hydrogen voltameter is also used. A convenient form is shown in Fig. 264. The two electrodes, which should be made of platinum to avoid chemical reaction between the electrodes and the products of electrolysis, are sealed into the two limbs of a U-tube. The limbs are graduated so that the volume of the gas evolved can be read off. The voltameter is completely filled with dilute sulphuric acid by means of a funnel, the taps are then closed, and the voltameter is ready for use. The mass of the hydrogen evolved is determined from the volume, its density being known.

If the current passing through the apparatus is constant, its value can be determined by the voltameter by allowing it to pass for a measured time t. Then since $m = e \cdot c \cdot t$, we have

$$c = \frac{m}{et}$$

If the current is not constant, c will be the average current through the voltameter during the time of the experiment.

331. Theory of Electrolysis.—There is much evidence, both chemical and physical, for believing that the molecule of an

electrolytic substance when dissolved in water dissociates or splits up into two or more atoms or groups of atoms (according to the nature of the substance), each of which carries an electric charge (Fig. 265). These charged systems are known as **ions.** It is found that the metals and hydrogen are always deposited in the cathode, or negative plate, while the acid particles and non-metals such as oxygen and chlorine appear at the anode. The former are therefore called electro-positive ions since they presumably carry positive charges; the latter are called electro-negative. Thus a solution of sodium chloride breaks up into ions of sodium and chlorine, the sodium ions carrying a positive, and the chlorine a negative charge. Since the electrolyte as a whole is neutral, the charge on the sodium ion is equal and opposite to that on the chlorine ion. It can be shown

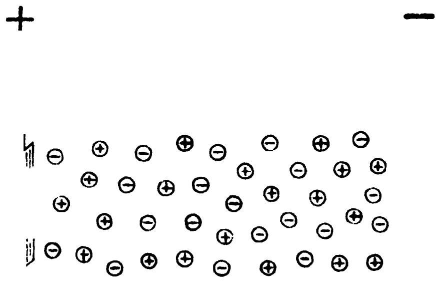


FIG. 265.—Theory of Electrolysis.

that all monovalent ions carry the same charge. Similarly, a solution of sulphuric acid breaks up into one *compound ion* (SO_4), which is negatively charged, and two hydrogen ions, each of which has a positive charge. The negative charge on the SO_4 ion must therefore be twice the positive charge on the hydrogen ion. The charge on a divalent ion is therefore twice the charge on a monovalent ion.

Let us consider now the electrolysis of a solution of sulphuric acid. The electrodes are maintained by the battery at a constant difference of potential, the anode being positive and the cathode negative. There is thus a field of electric force across the electrolyte, and the ions being charged begin to move, the negative to the anode and the positive to the cathode, with a velocity proportional to the field. Thus we have a steady drift of the positively charged ions in the direc-

tion of the cathode, and of negatively charged ions in the direction of the anode. But, as we have seen (§ 312), a motion of negative electricity from cathode to anode is equivalent to a motion of positive electricity in the opposite direction. Thus from the electrical point of view each of these drifts may be regarded as conveying positive electricity from anode to cathode—that is to say, the moving ions convey a current from the anode to the cathode through the solution.

Let m be the mass of the ion of one kind in the solution, and q the charge upon it; and let us suppose that in a given time t, n of these ions reach the electrode. Then the charge conveyed to the electrode is equal to $n.q$; while the mass of the substance deposited is $n.m$. The ratio of the mass of substance deposited to the quantity of electricity passed through the solution (*i.e.*, the electro-chemical equivalent) is

therefore $\frac{n.m}{n.q} = \frac{m}{q}$, and is constant for a given kind of ion.

The electro-chemical equivalent of a substance is therefore the ratio of the mass of a single ion of the substance to the charge upon it.

Now the mass of a given ion is proportional to its atomic weight, while the charge upon it is proportional to the valency. The electro-chemical equivalent $\frac{m}{q}$ is therefore proportional to the $\frac{\text{atomic weight}}{\text{valency}}$; that is, to the chemical equivalent. Our theory of electrolysis, therefore, gives a simple explanation of the experimental laws of Faraday.

332. Secondary Actions.—When an ion has given up its ionic charge to the electrode it resumes its ordinary chemical character, and may thus react either with the surrounding water or with the material of the electrode. For example, in the electrolysis of dilute sulphuric acid in a cell with platinum electrodes, the hydrogen, being unable to react with either the water or the electrode, is given off as a gas. On the other hand, the negative ion SO_4 reacts with the water surrounding the anode to form sulphuric acid and oxygen which is evolved. The total quantity of sulphuric acid therefore remains unchanged by the action of the current, and the experiment is often described as the electrolysis of water.

This description is incorrect. Pure water is not an electrolyte, and is practically a non conducto of electricity.

These reactions at the electrodes are known as *secondary actions*. They are of considerable importance, and may be very complicated.

333. Polarisation of the Electrodes.—If we attempt to pass a current through a hydrogen voltameter using a single voltaic cell, or a single Daniell cell, we shall find it impossible to do so. A momentary current passes at the first closing of the circuit, but rapidly dies away to nothing. This can be shown to be due to the production within the voltameter of a potential difference which acts in the opposite direction to that of the cell producing the current. When a current is passed through the voltameter the electrodes become coated with layers of oxygen and hydrogen respectively. These elements have a strong affinity for each other, and their tendency to combine is represented electrically by the existence of a potential difference between them. This potential difference can easily be demonstrated. If a current is sent through the voltameter for a little while to produce a coating of the gases on the electrodes, and the battery producing the current is disconnected, then on joining the two electrodes through a galvanometer a current will flow through the galvanometer from the oxygen to the hydrogen, and therefore through the acid in the voltameter from the hydrogen to the oxygen. The current will continue to flow until the layers of gas have recombined. This effect is known as *polarisation*.

It is obvious that to pass a continuous current through the voltameter we must apply a difference of potential to the plates greater than the polarisation potential, or *back electromotive force*, as it is often called. The back E.M.F. in a hydrogen voltameter is greater than the E.M.F. of a simple voltaic or a Daniell cell, but less than that of two such cells. Hence we can decompose water with two Daniell cells, but not with one.

It will be seen that the platinum plates when covered with oxygen and hydrogen behave in exactly the same way as the copper and zinc plates in a voltaic cell, the hydrogen plate corresponding to the zinc and the oxygen plate to the copper.

When the current is passed through the voltameter in the usual way, it is obvious that it is being forced through against

the back E.M.F. due to the polarised plates, and that the electricity is being transferred across the electrolyte from a low to a *high potential*. Consequently, work is being done (§ 294) in the cell, since the potential of the electricity is being raised. This work, which is supplied by the battery driving the current, provides the energy required to decompose the electrolyte.

EXAMINATION QUESTIONS.—XVII

1. State Faraday's laws of electrolysis. Describe how they may be tested experimentally.

2. What is the electro-chemical equivalent of a substance? Explain how the average current through a circuit may be found by means of a voltameter included in the circuit.

3. Describe briefly the way in which an electric current is conducted through a solution of copper sulphate. What weight of copper would be deposited from such a solution by the passage through it of 20 amperes for three hours? The electro-chemical equivalent of copper is 0·000328 gram per coulomb.

4. Distinguish between the chemical and the electro-chemical equivalents of a substance. A current of 3 amperes flowing through a solution of sulphate of copper for half an hour deposits 1·78 gram of copper (atomic weight, 63·6). Calculate the electro-chemical equivalent of hydrogen.

5. A constant current is passed through a silver voltameter and a tangent galvanometer connected in series, for twenty minutes. The weight of silver deposited is found to be 0·2 gram, and the deflexion of the galvanometer is 45°. Calculate the reduction factor of the galvanometer.

6. Explain why it is impossible to electrolyse acidulated water by the action of a single Daniell cell, and describe an experiment in support of your explanation.

7. Explain what is meant by the polarisation of an electrolytic cell, and describe an experiment to illustrate the effect. Why is there no polarisation when a solution of copper sulphate is electrolysed using copper terminals?

8. Calculate the cost for current of depositing 1 gram of copper by electrolysis, assuming that a current of 1 ampere can be obtained for one penny per hour. The electro-chemical equivalent of copper is 0·000328 gram per coulomb.

CHAPTER XI

THE VOLTAIC CELL. ELECTRO-MOTIVE FORCE

334. The Voltaic Cell. It has already been noted that if a plate of copper and a plate of zinc are immersed in dilute acid a difference of potential is set up between the two metals, which is maintained as long as the cell is in working order. This difference of potential is known as the **electro-motive force** of the cell, and depends on the nature of the two metals and the exciting fluid. Cells may be formed of other pairs of metals and with other electrolytic fluids between the plates. It is only necessary that the two metals should be different, and that one of them should be acted upon chemically by the liquid surrounding them.

The mechanism by which the potential difference is produced is not yet satisfactorily explained. The source of the energy of the current produced by the cell is the chemical energy liberated during the action of the exciting fluid on the metal. When zinc dissolves in sulphuric acid, energy is liberated in the form of heat. When, however, the action takes place in the voltaic cell, this energy is liberated not as heat but as the energy of the electric current. It is possible to calculate the electro motive force of a voltaic cell from a knowledge of the energy of the chemical changes which take place in the cell.

Since there is no accumulation of electrical charge at any point in a current circuit, the same quantity of electricity must flow across every cross-section of the circuit in a given time. The phenomenon is, in fact, very much like the flow of water through a closed system of pipes. Thus, as a current flows from the copper to the zinc plate along the wire joining them, it must complete the circuit by flowing from the zinc plate to the copper plate within the cell itself. Keeping to the hydrostatic analogy, we may regard the cell as a sort of

automatic pump taking in electricity at a low pressure and giving it out at a high pressure, and thus maintaining a circulation of electricity round the circuit. The difference in pressure on the two sides of such a pump is analogous to the electro-motive force of the cell.

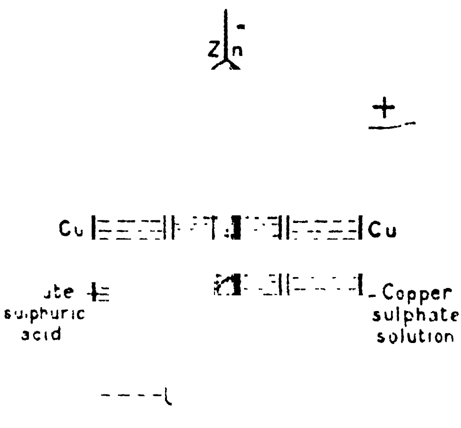
335. Polarisation of the Cell.—Since the liquid between the plates of the cell is an electrolyte and a current is passing through it, the plates tend to become polarised, in just the same way as the plates in a voltameter. Thus, in the case of the simple cell, hydrogen is deposited on the copper plate and forms a polarising layer on it. Now this polarising layer, as we have seen (§ 333), sets up a potential difference in the opposite direction to that which produces it. The current within the polarised cell tends to flow from the hydrogen to the zinc instead of from the zinc to the copper. On this account, as the hydrogen accumulates, the effective electro-motive force of the cell rapidly falls, and finally the cell ceases to furnish any useful current.

The presence of the layer of hydrogen, which is a bad conductor of electricity, also tends to reduce the current by interposing a badly conducting substance in the path of the current The current given by a simple cell thus rapidly falls to a very small value if the cell is used for any length of time.

336. Depolarisation.—The polarisation of a cell can obviously be prevented if we can ensure the removal of the polarising layer of hydrogen as fast as it is formed. A simple cell can be restored to action by taking out the copper plate and cleaning it. It can also be kept working by brushing off the hydrogen as it forms by some sort of scraper. These methods are obviously inconvenient. It is better to remove the hydrogen by surrounding the plate with some substance which will act upon the hydrogen chemically. The different forms of cell in common use are all designed to overcome the polarisation of the electrodes.

337. The Daniell Cell.—The most satisfactory arrangement is one due to Daniell. The zinc plate Z (usually a cylindrical rod) is contained in a porous pot P (Fig. 266) containing dilute sulphuric acid. The porous pot is placed in a wider copper vessel containing a saturated solution of copper sulphate. The copper vessel forms the copper plate of the cell, while the copper sulphate solution is the *depolarising fluid.* The porous pot prevents the mixing of the two fluids in the cell without interfering with flow of the current.

When a current is allowed to flow by joining the two poles of the cells, the acid acts upon the zinc, forming zinc sulphate, and liberating hydrogen ions which pass from the zinc towards the copper vessel. On entering the copper sulphate, however, the hydrogen ions replace the copper in the compound, forming sulphuric acid and liberating copper ions which travel on with the current, and are finally deposited on the copper vessel. Thus copper instead of hydrogen is deposited on the copper plate. As the nature of the plate is not changed, there is no polarisation.



Fi The Daniell Cell.

The Daniell cell gives a very constant electromotive force, and is much used in experiments where a constant current is required. Its disadvantages are that the E.M.F. of the cell is rather small, and that it requires to be taken to pieces when not in use.

338. The Bichromate Cell.—In this arrangement the hydrogen formed is oxidised by mixing an oxidising agent, potassium bichromate, with the sulphuric acid. As only one fluid is employed, no porous pot is required. As a mixture of sulphuric acid and bichromate acts

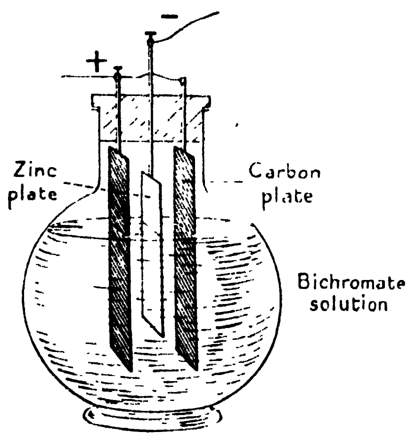


FIG. 267.—The Bichromate Cell.

on copper, the copper plate is replaced by one of carbon, which functions as the *positive* plate of the cell. As generally constructed (Fig. 267), the cell has two carbon plates, one on each side of the zinc plate. These carbon plates are connected together, and form the positive pole of the cell. The zinc is mounted on a long sliding rod, so that it can be drawn up out of the liquid when the cell is not in use. This cell has a large E.M.F., and is capable of producing a considerable current, which, however, is not so constant as that of the Daniell. The fluid is highly corrosive, and the zinc plate must be taken out of the solution as soon as the current is no longer required.

339. The Leclanché Cell.—The Leclanché cell differs from

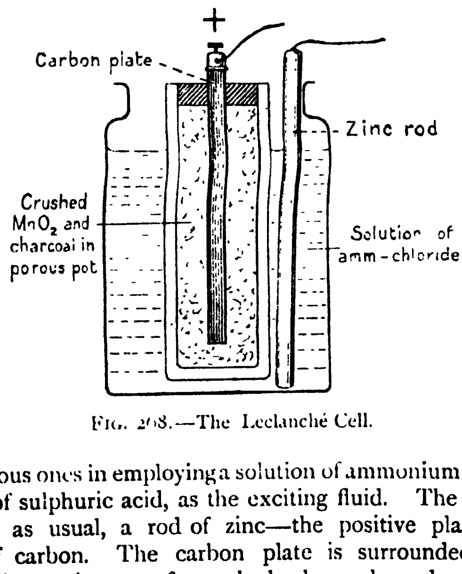


FIG. 268.—The Leclanché Cell.

the previous ones in employing a solution of ammonium chloride, instead of sulphuric acid, as the exciting fluid. The negative plate is, as usual, a rod of zinc—the positive plate being made of carbon. The carbon plate is surrounded with a depolarising mixture of crushed charcoal and powdered manganese dioxide, which gradually oxidises the free hydrogen into water. This mixture may either be contained in a porous pot (Fig. 268) or compressed into a solid mass around the carbon plate.

The depolarising action of the solid mixture is slow, so that if the current is allowed to flow for any length of time the cell becomes polarised. The polarisation is gradually destroyed if the cell is allowed to stand. The Leclanché

cell is, therefore, not suitable for continuous work. It has, however, the great advantage that the exciting fluid has no action upon the zinc when the current is not flowing. The cell can, therefore, be left in working order for any length of time without deterioration, and is thus exceptionally useful for such purposes as ringing electric bells, or working a telephone.

The "dry" cell, now so largely used in flash lamps, is practically a Leclanché cell, in which the ammonium chloride is mixed with plaster, zinc chloride, and flour. This sets into a porous mass, and the cell can thus be carried about without fear of spilling.

340. The Accumulator, or Secondary Cell.—In the cells we have just described the current is produced by the consumption of the zinc plate, which is chemically acted upon by the exciting fluid. It is much more economical to produce an electric current by the action of machines known as dynamos or generators (§ 367), and all the current used commercially is generated in this way. For many purposes, however, a more portable source of current is required. The difficulty can be solved by the use of an accumulator.

If we pass a current through a hydrogen voltameter, we have seen that a current may afterwards be obtained from it by joining the electrodes by a wire. The instrument acts as a cell, and is in fact a sort of accumulator or secondary battery. Part of the energy given to the apparatus by the primary electric current is stored in it in the form of chemical energy, and is transformed again into electrical energy when the electrodes are joined. As the quantity of gas which can be condensed on the electrodes is small, this form of secondary cell is of no practical use.

The ordinary accumulator consists of two lead plates, stamped in the form of grids and packed with lead oxide. If a pair of these is immersed in sulphuric acid, and a current passed from one to the other, chemical changes take place in the plates, resulting in the formation of lead peroxide on the one plate and of metallic lead on the other. If the charging current is stopped, and the plates joined by a wire, a current flows through the wire from the highly oxidised plate to the oxidisable plate, just as it flowed in the polarised voltameter from the oxygen to the hydrogen.

If the current is allowed to flow, the condition of the two

plates changes, the positive plate being reduced to lead oxide, while the negative plate becomes oxidised again. It must be noted that the energy is not stored in the accumulator in an electrical form. It is converted into chemical energy, and only resumes its electrical form when the call is allowed to give a current.

The electro-motive force of the accumulator is practically constant during the greater part of the discharge, and only begins to fall when the accumulator is nearly exhausted. The cell can then be recharged by passing a current through it. The E.M.F. is high, being equal to twice that of a Daniell cell. The quantity of electricity which can be obtained from such a cell after a full charge is proportional to the area of the plates, and is very considerable. Accumulators made to fit an ordinary pocket flash lamp will furnish a current of half an ampere for ten hours on a single charge; while the larger batteries used for motor-car ignition, etc., will give a current of 1 ampere continuously for forty hours.

341. Units of Potential Difference, and Electro-Motive Force. - The difference of potential between two points has been defined (§ 294) as the work done in moving unit quantity of electricity from the one point to the other against the electric field. Two points are said to be at unit difference of potential if 1 erg of work is expended in moving 1 unit of charge from one point to the other. The magnitude of the unit, therefore, depends on the size of the unit of charge.

On the absolute electro-magnetic system of units—*Unit difference of potential is the potential difference existing between two points when 1 erg of work is spent in moving 1 absolute electro-magnetic unit of charge from the one point to the other.*

This unit of potential difference is very small indeed, being rather less than one hundred-millionth of the potential difference between the poles of a Daniell cell. For practical purposes a potential difference equal to one hundred million (10^8) times the absolute unit is taken as the unit of potential difference. It is known as the **volt.**

Thus—

1 VOLT = 10^8 Absolute Electro-Magnetic Units of Potential.

ELECTRO-MOTIVE FORCE is often used as equivalent to potential difference. Strictly speaking, *the electro-motive force of a battery is the potential difference between its poles when on*

open circuit—that is to say, when the poles are not connected by a conductor and consequently the cell is giving no current It is often used loosely as simply equivalent to potential difference. Since, in either case, electro-motive force is a potential difference, it is measured in the same units—that is, in volts.

Since the potential difference is measured in volts it is often spoken of as the **voltage.** The E.M.F. of a Daniell cell is 1·08 volt: that of a Leclanché about 1·4 volt; and that of an accumulator, 2·2 volts when fully charged. Instruments have been designed which measure potential difference directly in volts. They are known as voltmeters.

342. **Electrical Energy and Power.**—It follows immediately from our definition of unit potential difference that the work done in moving a quantity of electricity Q through a difference of potential E is given by

$$W = E \cdot Q \text{ ergs}$$

when E and Q are both measured in absolute units. Now the practical unit of charge, the **coulomb,** is one-tenth of the absolute unit, while the practical unit of potential difference is 10^8 absolute units. Hence the work W done in moving 1 coulomb through a potential difference of 1 volt is given by

$$W = 10^8 \times \frac{1}{10} = 10^7 \text{ ergs}$$

The work done when 1 *coulomb is moved through a potential difference of* 1 *volt is known as a* **joule.** *The joule is thus the practical electrical unit of work or energy, and*

$$\mathbf{1\ JOULE = 10^7\ ergs}$$

By the conservation of energy work will be done by the electricity if it is allowed to flow from the higher to the lower potential. Thus 1 coulomb of electricity in falling through a potential difference of 1 volt is capable of furnishing 1 joule—that is, 10^7 ergs of work.

Since a coulomb is the quantity of electricity passing when a current of 1 ampere flows for 1 second, $Q = C \cdot t$ where C is the current in amperes and t the time of flow in seconds. Hence the work done by a current C amperes flowing for t seconds between two points differing in potential by E volts is given by

$$\begin{aligned} W &= E \cdot C \cdot t \text{ joules} \\ &= E \cdot C \cdot t \times 10^7 \text{ ergs} \end{aligned}$$

Power is the rate of doing work (§ 38). Hence electrical power is the rate at which the electrical current is doing work. The unit of electrical power is the **watt.**

The watt is the power expended when the current is doing work at the rate of 1 **joule** *per second.*

It is, therefore, the rate of working in a circuit when a current of 1 ampere is flowing between two points at a potential difference of 1 volt.

In engineering, a **kilo-watt,** or 1000 watts, forms a suitable unit of power. The energy supplied by a circuit working at the rate of 1 kilo-watt for one hour is known as the **kilo-watt hour,** or the **Board of Trade unit,** and is the "unit" mentioned in the quarterly accounts of electric supply companies. It is obviously a unit of energy, and is equal to $10^3 \times 60 \times 60$—that is, $3{\cdot}6 \times 10^6$ joules, or $3{\cdot}6 \times 10^{13}$ ergs.

CHAPTER XII

OHM'S LAW—RESISTANCE

343. Resistance in Conductors.—Although a conducting metallic wire allows a current to pass through it, it does not do so without impeding the free flow of the electricity to a greater or smaller extent. Thus, if we connect a Daniell cell in series with a tangent galvanometer by pieces of short thick wire, and, after noting the deflexion, substitute for one of the short wires a long piece of thin wire, the deflexion in the second case will be less than in the first. The electro-motive force of the cell remains the same, but the current supplied by it is reduced. The same E.M.F. produces a smaller current in the long thin wire than in the short thick wire. In other words, the wire, though a conductor, offers resistance to the passage of the current.

344. Relation between Current and Potential Difference.—Suppose we take a metallic conductor, say, for example, a long copper wire, and connecting it in series with an ammeter or tangent galvanometer to measure the current, pass a current through it from a constant battery. As electricity is flowing from one end of the wire to the other it is obvious that a difference of potential exists between its ends. This difference of potential can be measured by means of a quadrant electrometer (§ 299). Quadrant electrometers are now made sufficiently sensitive to record a potential difference of as little as a thousandth of a volt, and the measurement can thus be made with considerable accuracy.

Let us now increase the current through the wire (by increasing the number of cells in the circuit), and again measure both the current and the potential difference between the ends of the wire. It will be found that if the current is doubled, the potential difference is also doubled; if the current is trebled, the potential difference is also trebled, and so on. In fact, the potential difference between the ends of

the given conductor is directly proportional to the current flowing through it. The experiment can be repeated with other metallic conductors of different sizes, materials, and shapes; or it may be varied by taking a conducting wire and connecting *any two points* on it to the terminals of the quadrant electrometer. If the wire is uniform and the current remains constant, it will be found that the potential difference is directly proportional to the length of wire between the points. For the same two points, however, it will be found that the potential difference between them will be directly proportional to the current flowing through the wire.

For a given conductor the ratio of the potential difference between its ends to the current flowing through it is a constant for the conductor under given physical conditions.

This important relation is known as **Ohm's law.**

Thus, if E is the difference of potential between the ends of a conductor, and C the current in it, then, by Ohm's law,

$$\frac{E}{C} = \text{constant}$$

Further, if E is the potential difference between *any two points* on a conductor carrying a current C, then $\frac{E}{C}$ is a constant for the given two points under given physical conditions.

Since the potential difference between two points is the electrical condition which determines the flow of electricity from one to the other, we may regard the current in the conductor as being caused by the difference of potential between its ends. In other words, we may regard this potential difference as an electro-motive force acting along the conductor. Ohm's law thus shows us that—

The current produced in a given conductor is directly proportional to the applied electro-motive force.

345. Definition of Electrical Resistance.—The important ratio $\frac{E}{C}$, which, as we have seen, is a constant for a given conductor, will serve as a measure of the resistance offered by the conductor to the passage of the current. If the conductor offers much resistance to the passage of the current, then a large E.M.F. will be required to produce a given current in it, and the ratio $\frac{E}{C}$ will be large. On the other

hand, if the conductor offers little resistance to the current, a comparatively small E.M.F. will be sufficient to produce a considerable current through it, and the ratio $\frac{E}{C}$ will be small.

The ratio of the electro-motive force between the ends of a given conductor to the current passing through it is known as the **electrical resistance** *of the conductor.*

The electrical resistance of a conductor is thus defined as the ratio of the potential difference between its ends to the current passing through it.

By Ohm's law this ratio is a constant for a given conductor under given physical conditions.

FIG. 269. -Conductors arranged in Series.

Thus, for a given conductor,

$$\frac{E}{C} = R$$

where R is by definition the resistance of the conductor. This relation may also be expressed in the forms

$$E = C \cdot R$$

and

$$C = \frac{E}{R}$$

A conductor is said to have unit resistance if unit difference of potential between its ends produces unit current in it.

On the practical system of units a conductor will have unit resistance if a difference of potential of 1 volt between its ends produces a current in it of 1 ampere.

This unit of resistance is known as the **ohm**. Thus—

$$\frac{E\ (\text{volts})}{C\ (\text{amperes})} = R\ (\text{ohms})$$

346. Resistance of Conductors in Series.—If a number of conductors are connected end to end, so that the current flows in succession through each of them, they are said to be connected in series. Thus the wires AB, BC, CD in Fig. 269 are connected in series. Since there is no accumulation

of electricity anywhere in the electric circuit the same current will flow in each of the conductors.

Let E_a, E_b, . . . be the potentials of the points A, B, . . . and let r_1, r_2, . . . be the resistances of the conductors AB, BC, . . . Then the potential difference between A and B is $E_a - E_b$ and by Ohm's law we have

$$E_a - E_b = Cr_1$$

where C is the current passing through the conductors. Similarly—

$$E_b - E_c = Cr_2$$
$$E_c - E_d = Cr_3$$

Hence the whole difference of potential E between the ends of the system

$$\begin{aligned} &= (E_a - E_b) + (E_b - E_c) + \ldots \\ &= Cr_1 + Cr_2 + \ldots \\ &= C\,(r_1 + r_2 + \ldots) \end{aligned}$$

But by definition $\frac{E}{C} = R$, where R is the resistance of the *system* of conductors. Hence—

$$R = r_1 + r_2 + \ldots$$

The resistance of a number of conductors in series is equal to the sum of their separate resistances.

347. Resistance of a Number of Conductors in Parallel.—If the same two points are connected by two or more conductors so that the current may pass from one point to the other by two or more paths, the conductors are said to be *in parallel* or less usually *in multiple arc.*

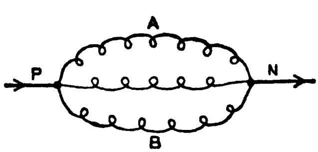


FIG. 270.—Conductors arranged in Parallel.

Thus A, B, and C (Fig. 270), each of which joins the points P and N, are said to be in parallel. In this case the potential difference between the ends of each of the conductors is the same, but currents of different magnitude flow down the three paths. Let c_a be the current in A, and c_b and c_c those in B and C, while r_a, r_b, r_c are the resistances of the conductors A, B, and C. The current C flowing in at the point P divides into three branches to reunite again at N. The quantity of electricity flowing in at P in a given time must be equal to the quantity flowing out through the paths A, B,

and C in the same time, since there is no accumulation of charge at P. Hence—

$$C = c_a + c_b + c_c$$

Also, if E is the potential difference between P and N, we have, applying Ohm's law to each of the conductors,

$$c_a = \frac{E}{r_a}; \quad c_b = \frac{E}{r_b}; \quad c_c = \frac{E}{r_c}$$

$$\begin{aligned} \therefore C &= c_a + c_b + c_c \\ &= \frac{E}{r_a} + \frac{E}{r_b} + \frac{E}{r_c} \\ &= E\left(\frac{1}{r_a} + \frac{1}{r_b} + \frac{1}{r_c}\right) \end{aligned}$$

But, if R is the resistance between P and N, $C = \frac{E}{R}$

$$\therefore \frac{1}{R} = \frac{1}{r_a} + \frac{1}{r_b} + \frac{1}{r_c}$$

The reciprocal of the resistance of a number of conductors in parallel is equal to the sum of the reciprocals of the separate resistances.

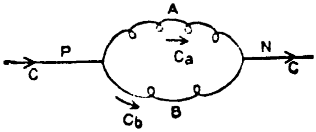


FIG. 271.—Theory of Shunts.

The reciprocal of the resistance is termed the **conductance** of the conductor.

348. Theory of Shunts.—If two conductors PAN and PBN (Fig. 271) are connected in parallel, the current C in the circuit will divide itself between them according to their resistance. Let C_a and C_b be the currents in the conductors PAN and PBN, and r_a and r_b their resistances. Since there is no accumulation of electricity at any point, the current C flowing into P must be equal to the sum of the currents flowing away from P, that is—

$$C = C_a + C_b$$

By Ohm's law, the potential difference between P and N is equal to $C_a r_a$ if we consider the conductor PAN, and also to $C_b r_b$ if we consider PBN. Thus—

$$C_a r_a = C_b r_b$$

$$\therefore \frac{C_a}{C_b} = \frac{r_b}{r_a}$$

The current in the conductors is inversely proportional to their resistances.

If we substitute the value of C_b obtained from this equation in the former one, we have

$$C = C_a + \frac{r_a}{r_b} . C_a$$

$$C_a = \frac{r_b}{r_a + r_b} . C$$

The conductor PBN is called a shunt circuit, or simply a **shunt** across the ends of the conductor PAN, which in turn is said to be *shunted* by the conductor PBN. For example, if PAN represents a galvanometer, or ammeter, and PBN a resistance coil connecting the terminals of the instrument, the instrument is said to be shunted by the resistance PBN.

It will be seen that the effect of shunting a galvanometer is to reduce the current passing through it by a definite fraction, which can be calculated if the resistances of the galvanometer and its shunt are known. If G is the resistance of the galvanometer and S that of the shunt across its terminals, our equation shows us that the current in the galvanometer is given by

$$C_g = \frac{S}{G + S} . C$$

where C is the current in the circuit.

This result is frequently applied to reduce the sensitiveness of an ammeter or galvanometer in a known ratio. Thus if we have an ammeter which reads up to 1·5 ampere, and we shunt it with a resistance exactly $\frac{1}{9}$th that of the ammeter itself, the current in the ammeter is reduced to $\frac{S}{G+S}$, that is, $\frac{\frac{1}{9}G}{G+\frac{1}{9}G}$ or $\frac{1}{10}$th of the current in the main circuit. Thus a reading of 1·5 when the ammeter is shunted corresponds to $1{\cdot}5 \times 10$, *i.e.*, 15 amperes in the main circuit. The range of the instrument can thus be increased to any desired extent by the use of a proper shunt. Such shunts are generally supplied with the instrument by the makers.

349. Specific Resistance.—It can be shown by experiment that the resistance of a uniform wire is directly proportional to its length, and inversely proportional to its area of cross-section. It also depends on the nature of the substance from which

the wire is made. Thus if l is the length of the wire, α its area of cross-section, its resistance R is given by the equation

$$R = \sigma . \frac{l}{\alpha}$$

where σ is a constant depending only on the material of the wire, and is known as the **specific resistance.**

The specific resistance of a substance is the resistance offered by a cube of 1 *cm. edge of the substance to a current flowing through it parallel to one of the edges.*

350. Current in a Complete Circuit.—The current which will be produced in a given circuit by a given battery can be calculated by Ohm's law. If E is the electro-motive force of the battery (that is, the potential difference between its poles on open circuit) and R the total resistance of the circuit, the current C will be given by the relation

$$C = \frac{E}{R}$$

In using the equation it must not be forgotten that the battery itself offers a resistance to the current. Thus if R' is the total resistance of the conductors joining the poles of the cell, it is found that the current C is *not* equal to $\frac{E}{R'}$, but to $\frac{E}{R'+B}$, where B is a constant which depends upon the battery. It measures the resistance which the battery itself offers to the current, and is known as the **internal resistance** of the battery. This resistance must be taken into account in calculating the current which the battery will give. Its value depends upon the kind of battery used. Thus, if a circuit consists of a battery of E.M.F. E and internal resistance B, a conductor of resistance R, and, say, an ammeter of resistance R', then the current in the circuit is given by

$$C = \frac{E}{R + R' + B}$$

The internal resistance of a single cell depends upon the way it is made up. It is usually of the order of 1 ohm. Thus the maximum current which can be obtained from, say, a Daniell cell with an E.M.F. of 1·08 volt and an internal

resistance of 1 ohm would be 1·08 ampere. Accumulators have a very small internal resistance, and hence should never be short-circuited, as the large current which would result would seriously damage the plates.

351. Combination of Cells in Series and in Parallel.—If a number of cells are connected in series (that is to say, with the positive plate of the one cell joined to the negative plate of the next, and so on), the E.M.F. of the whole battery is equal to the sum of the E.M.F.'s of the individual cells.

If a number of similar cells are connected in parallel (that is, with all their positive poles connected together and all their negative poles connected together), the system is equivalent to a single cell but with plates of much larger size. The E.M.F. of the battery is thus equal to that of a single cell.

The current produced by either of these arrangements through a conductor of resistance R can be calculated by Ohm's law. Let there be n cells each of resistance b and E.M.F. e.

I. CELLS IN SERIES.—The E.M.F. of the battery will be the sum of the separate E.M.F.'s, that is, $n \,.\, e$, and the resistance of the battery will be the sum of the separate resistances of the cells, that is, $n \,.\, b$. The current C produced through an external resistance R will therefore be given by

$$C = \frac{n \,.\, e}{R + n \,.\, b}$$

II. CELLS IN PARALLEL.—The E.M.F. of the battery will be simply that of any one of the cells, that is, e. The resistance of the battery, however, will be that of n equal conductors each of resistance b connected in parallel, that is, $\frac{b}{n}$.

The current C produced through an external resistance R will be given by

$$C = \frac{e}{R + \frac{b}{n}} = \frac{n \,.\, e}{nR + b}$$

Which of the two arrangements, series or parallel, will send the bigger current through a given resistance depends upon the value of the latter. If it is large, compared with the resistance of the cells, the series arrangement will pro-

duce the greater current; on the other hand, if the external resistance is small compared with that of one of the cells, the parallel arrangement will be more effective. The most effective arrangement in a given case can be found by substituting the values in the equations above.

EXAMPLES.

1. The current from a dynamo is passed through a wire having a resistance of $\frac{1}{10}$th ohm, and produces a potential difference of 1·4 volt between its ends. What is the strength of the current?

2. A metallic filament lamp working on a 200-volt circuit takes a current of $\frac{1}{4}$ ampere. What is its resistance?

3. Show that the resistance of three equal resistance coils when arranged in series is nine times their resistance when connected in parallel.

4. Five metallic filament lamps each of 500 ohms resistance are connected in multiple arc across a 200-volt circuit. Calculate the resistance and the total current passing through the lamps.

5. An ammeter, which has a resistance of 1 ohm, is graduated in thousandths of an ampere. With what resistance must it be shunted to make each graduation correspond to $\frac{1}{10}$th ampere?

6. The specific resistance of copper is $1·6 \times 10^{-6}$ ohms per cm. cube. Calculate the resistance of a copper wire 1 metre long and $\frac{1}{5}$th mm. in diameter.

7. An iron wire 1 metre long and 1 mm. in diameter has a resistance of 0·123 ohm. What is the specific resistance of iron?

8. Three Leclanché cells each of E.M.F. 1·4 volt and resistance $\frac{1}{2}$ ohm are provided. How should they be connected, in series or in parallel, to produce the greatest current through a resistance of (*a*) $\frac{1}{10}$th ohm, (*b*) 10 ohms?

9. What is the resistance of a 200-volt 20-watt lamp?

10. It is required to re-charge a battery of 20 accumulators each of which has a voltage of 1·8 volt and an internal resistance of 0·1 ohm from a 100-volt circuit. What resistance must be placed in series with the battery in order that the charging current may be 4 amperes?

CHAPTER XIII

MEASUREMENT OF RESISTANCE AND ELECTRO-MOTIVE FORCE

352. Measurement of the Resistance of a Conductor.—The resistance of a conductor can be measured directly from the definition if we are furnished with an ammeter and a voltmeter. Connect the conductor AB (Fig. 272) in series with a suitable battery and an ammeter, and connect the ends A and B of the conductor to the terminals of the volt-

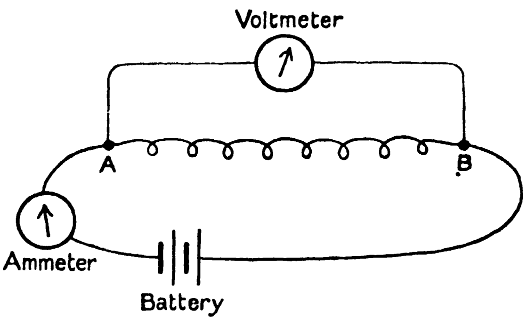


FIG. 272.—Measurement of Resistance by Voltmeter and Ammeter.

meter. The current C can be read on the ammeter while the potential difference between A and B is registered on the voltmeter. The resistance of AB is then given by

$$R=\frac{E}{C}$$

Thus, if the current is found to be 2·5 amperes, and the potential difference across the ends of the conductor is 7·5 volts, the resistance of the conductor is $\frac{7\cdot5}{2\cdot5}$, that is, 3 ohms

In practice it is more accurate to measure the resistance of an unknown conductor by comparison with that of a conductor of known resistance.

353. Resistance Boxes.—A length of wire C (Fig. 273) has its ends connected to two terminals A and B, on a wooden bobbin D. The wire, which is insulated by a covering of silk thread, is bent back upon itself as shown in the figure, and then wound upon the bobbin, the layers being protected by a final covering of wax. This arrangement forms what is known as a resistance coil, or simply a resistance. The length of the wire is adjusted by the maker so that the resistance between the terminals has some definite known value which is stamped upon the bobbin.

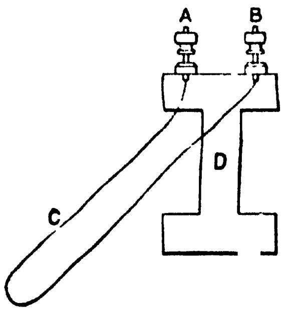


FIG. 273. Construction of a Resistance Coil.

A set of such resistances are often mounted in a box, known as a resistance box (Fig. 274). In this case the ends

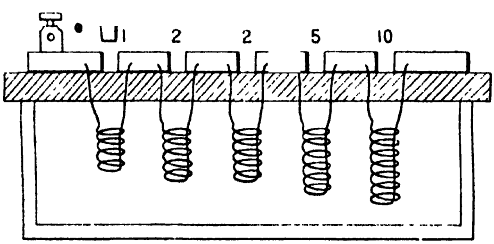


FIG. 274.—Construction of a Resistance Box.

of the wires are soldered to a succession of brass blocks on an ebonite slab, arranged so that the gaps between the blocks can be closed by metal plugs. If all the gaps are thus filled up, the current flows from one terminal of the box to the other, entirely through the brass blocks and plugs. These, being very thick, have a negligible resistance. If, how-

ever, one of the plugs is withdrawn, the current is compelled to flow through the corresponding resistance coil, and its resistance is added to the circuit. If all the plugs are withdrawn, the current passes through all the resistances in series, and the total resistance in the box is then the sum of the separate resistance coils. The resistances are usually graded like a set of weights, so that by withdrawing the proper plugs any resistance can be obtained from that of the smallest coil up to the whole resistance of the box.

354. Comparison of Resistances by a Tangent Galvanometer, or Ammeter.—Connect a resistance box in series with a tangent galvanometer, or ammeter, and a battery of constant E. M. F., *e.g.*, a Daniell cell. Make a series of observations of the current flowing through the circuit with different resistances in the box. The current will, of course, decrease as the resistance of the box is increased. A curve can now be plotted, showing the relation between the resistance in the box and the reciprocal of the current through the ammeter, or galvanometer. Since $R = \frac{E}{C}$, and E is constant, this curve will be a straight line, as shown in Fig. 275. The straight line will not pass through the origin, because when there is no resistance in the box there is still resistance in the circuit, namely, that of the battery and the galvanometer, both of which offer resistance to the current. The current therefore has a finite value even when there is no resistance in the box. If the line is produced to cut the axis of resistances in X, then OX measures the resistance of the battery and galvanometer on the scale of the curve.

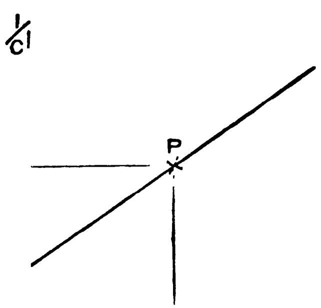


FIG. 275.—Measurement of Resistance by Tangent Galvanometer—Relation between R and $\frac{1}{C}$

To find the value of a given unknown resistance, remove the box from the circuit, substitute the unknown resistance in its place, and find the corresponding value of $\frac{1}{C}$. Mark this on the curve. The corresponding value of the resistance can then be read off on the horizontal axis. Thus if OA is the value of $\frac{1}{C}$, the corresponding point on the curve is P, and ON is the value of the unknown resistance.

As relative measurements only of the current are required, it is not necessary to know the reduction factor of the galvanometer. It will suffice to plot the values of $\frac{1}{\tan \delta}$ where δ is the deflexion of the galvanometer along the vertical axis, and the corresponding values of *R* along the horizontal axis.

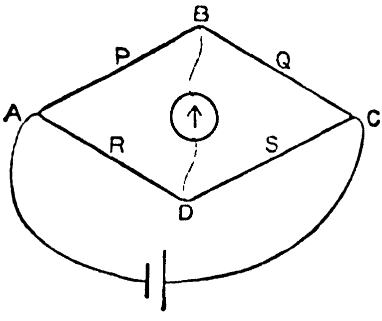


FIG. 276.—Principle of the Wheatstone Bridge.

355. Comparison of Resistances by the Wheatstone Bridge.—Let ABC and ADC (Fig. 276) be two conductors in parallel. The potential along each conductor falls from A to C. Hence, if we take any point B on the conductor ABC it will be possible to find some point on ADC which has the same potential as B. This can be done experimentally by connecting B through a sensitive galvanometer to a point D on ADC, and moving the connector about until there is no current flowing through the galvanometer. When this is the case, B and D must be at the same potential, otherwise, since BD is a conductor, a current would flow from the higher to the lower of the two potentials.

Suppose that the point D has been found. Let c_1 be the current along the conductor AB, and c_2 that along AD. There is no current along BD, and hence the current in BC is equal to that in AB, and the current in DC to that in AD. Let E_a, E_b, E_c, and E_d be the potentials at the points A, B,

C, and D, and let P, Q, R, and S be the resistances of the four arms AB, BC, AD, and DC. Then, applying Ohm's law to each of the conductors,

$$E_a - E_b = c_1 P$$
$$E_a - E_d = c_2 R$$

But, since the $E_b = E_d$,

$$E_a - E_b = E_a - E_d$$
$$\therefore\ c_1 P = c_2 R$$
$$\frac{P}{R} = \frac{c_2}{c_1}$$

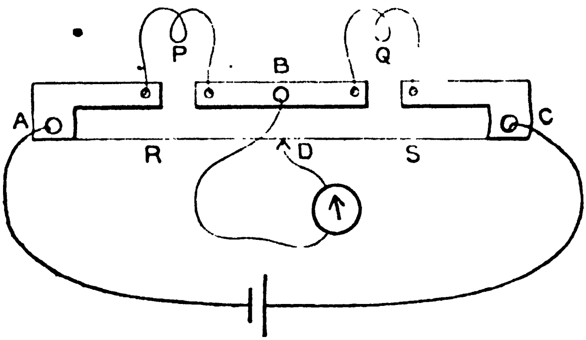


FIG. 277. -The Wheatstone Bridge.

Similarly, since $E_b - E_c = E_d - E_c$,

$$c_1 Q = c_2 S$$
$$\frac{Q}{S} = \frac{c_2}{c_1}$$
$$\therefore\ \frac{P}{R} = \frac{Q}{S} \text{ or } \frac{P}{Q} = \frac{R}{S}$$

Hence, if three of these resistances are known, the fourth can be calculated.

The experiment can be carried out with a Wheatstone bridge. This is shown diagrammatically in Fig. 277. A thick flat copper strip ABC of negligible resistance is furnished with two gaps, which can be bridged over by resistance coils P and Q. A long uniform wire is stretched between A and C. A battery is connected to A and C, and a galvanometer to a terminal B between the gaps. The remaining terminal of the galvanometer is joined to a sliding contact

which can be arranged to make contact with any point of the wire AC.

The current is allowed to pass, and the sliding contact moved along the wire until some point D is found at which there is no deflexion in the galvanometer. This point D is then at the same potential as B.

If P and Q are the resistances of the two coils, and R and S those of the portions AD and DC of the wire respectively, then, by the above analysis,

$$\frac{P}{Q}=\frac{R}{S}$$

(The two diagrams are lettered to correspond.) But the

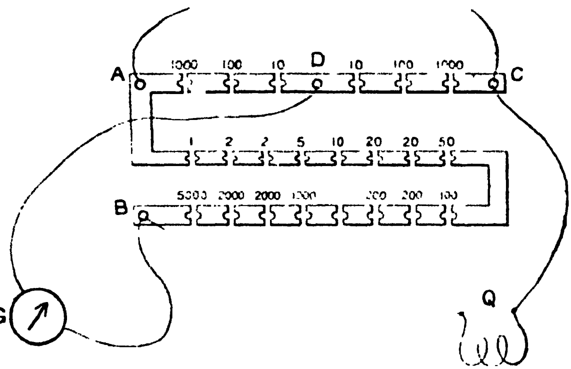


FIG. 278.—Determination of Resistance by the P.O. Box.

resistance of a uniform wire is proportional to its length. Hence, if d_1 and d_2 are the lengths of the portions AD and DC of the stretched wire, $\frac{R}{S}=\frac{d_1}{d_2}$. Hence finally—

$$\frac{P}{Q}=\frac{d_1}{d_2}$$

d_1 and d_2 can be measured on a metre scale fastened alongside the wire. Thus, if Q is a resistance coil of known resistance, the value of the resistance of the coil P can be determined.

356. The Post-Office Box.—The principle of the Wheatstone bridge can also be carried out with a special box of

resistance coils, first designed for the measurement of the resistance of telegraph wires, and known as the *post-office box.* It is shown diagrammatically in Fig. 278, which is lettered to correspond with the previous diagrams, and shows the relation between them. The arms AD and AC are known as ratio arms, and the ratio of $\frac{R}{S}$ can be made either 1 : 1, 10 : 1, or 100 : 1, as required, by withdrawing the proper plugs. The remaining arm of the box is arranged to give any whole number of ohms from 1 to 10,000. As before, the battery is connected from A to C, and the galvanometer from B to D, the unknown resistance being connected from B to C to form the fourth arm of the bridge. For convenience, a tapping key is inserted in the galvanometer circuit. Comparing the arrangement with the previous diagrams, we see that the condition that there shall be no current in the galvanometer circuit is given by

$$\frac{P}{Q}=\frac{R}{S}$$

The values of P, R, and S can be read off on the box.

If we start with the ratio arms equal, by taking out, say, 10 ohms in each, a balance will be obtained when the resistance in P is equal to the unknown resistance Q. As, however, the box is graduated by steps of 1 ohm, it will not usually be possible to get an exact balance. We shall find that the resistance required lies between two values differing by 1 ohm—say, between 6 and 7 ohms. To obtain a closer approximation, we make the ratio $\frac{R}{S}$ equal to 10 : 1, so that P must equal 10Q for a balance. Since Q lies between 6 and 7 ohms, P must now be between 60 and 70 ohms for the bridge to be balanced. By removing the intermediate plugs, we find that the balance point is, say, between 63 and 64 ohms. The value of Q thus lies between 6·3 and 6·4 ohms. By making the ratio arms 100 : 1, a second decimal place can be obtained.

357. Comparison of E.M.F.'s by the Tangent Galvanometer. —If a battery of E.M.F. E_1 is connected in series with a tangent galvanometer, the current through the galvanometer will be given by

$$C_1=\frac{E_1}{R_1}$$

where R_1 is the resistance of the whole circuit—that is, of the galvanometer, battery, and connecting wires. Similarly, if a second battery of E.M.F. E_2 is substituted for the first, the current C_2 will be given by

$$C_2 = \frac{E_2}{R_2}$$

where R_2 is the resistance of the circuit.

Now the resistances of different batteries are not necessarily the same, so that we cannot assume that R_2 is equal to R_1. On the other hand, the resistance of a battery is generally quite small (1 or 2 ohms), so that if the galvanometer used has itself a high resistance, the resistance of the battery will be negligible in comparison. Thus, with a high resistance

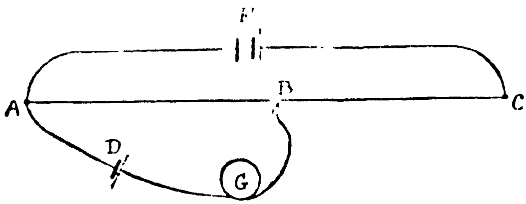


FIG. 279.—The Potentiometer.

galvanometer (say, 400 ohms), we may without appreciable error put $R_2 = R_1$, whatever the nature of the battery. Under these circumstances, we have

$$\frac{C_2}{C_1} = \frac{E_2}{R_2} \div \frac{E_1}{R_1} = \frac{E_2}{E_1}$$

For a tangent galvanometer where $C = k \tan \theta$, we have

$$\frac{E_2}{E_1} = \frac{\tan \theta_2}{\tan \theta_1}$$

The instrument known as a voltmeter is merely an ammeter or galvanometer of very large resistance. The current through the instrument is proportional to the voltage across its terminals; the scale is graduated to read directly in volts.

358. The Potentiometer.—If a constant current is passed along a uniform stretched wire AC (Fig. 279), the potential difference between A and some other point B on the wire is, by Ohm's law, equal to the product of the current into the resistance between the two points. Now the resistance of a

portion of uniform wire is directly proportional to its length, so that, if the current is constant, the potential difference between A and B is proportional to their distance apart as measured along the wire.

Thus, if A and B are joined by a second circuit containing a galvanometer G, there will be a current through the galvanometer owing to this difference of potential. If, however, we introduce into this branch circuit a cell D of E.M.F. E_1, so that its E.M.F. is in the opposite direction to that due to the current (*i.e.*, in the direction BDA), the resultant E.M.F. in the circuit ADB will be the difference between that existing between A and B and the E.M.F. of the cell. By suitably adjusting the distance between the points A and B, and including a greater or smaller length of the wire between them, we can make the potential difference between A and B exactly equal to that of the cell. The equality can be tested by watching the readings of the galvanometer G in the circuit ADB. When no current flows through the galvanometer, the E.M.F. E_1 of the cell must be exactly equal to the potential difference between A and B.

If now a second cell of E.M.F. E_2 is substituted for the first in the circuit ADB, and the point of contact moved along the wire AC until the position B′ is found, for which there is again no current in the galvanometer, then E_2 is equal to the potential difference between the points A and B′. Thus we have

$$\frac{E_2}{E_1} = \frac{\text{P.D. between A and B}'}{\text{P.D. between A and B}}$$
$$= \frac{d_2}{d_1}$$

where d_2 and d_1 are the distances AB′ and AB respectively, measured along the uniform wire AC. The E.M.F.'s of different cells can thus be compared. This arrangement is known as a **potentiometer.**

The fall of potential along the whole wire AC must obviously be greater than the E.M.F. of any of the cells to be compared, as otherwise a balance could not be obtained on the wire. The E.M.F. of the battery F supplying the current in AB must therefore be greater than that of the cells to be compared. The current supplied by this battery must remain constant during the experiment. A couple of accumulators connected in series will generally be found sufficient.

EXAMINATION QUESTIONS.—XVIII

1. Explain what is meant by the difference of potential between two points. What conditions must hold in order that two points on a copper wire may remain at a difference of potential?

2. Explain why the simple voltaic cell is unsatisfactory as a source of current. Describe some efficient form of voltaic cell, explaining the changes which go on in it.

3. What is meant by the polarisation of a battery? Describe some of the ways in which it can be eliminated.

4. Describe the construction of an accumulator (storage cell), and give an account of the actions taking place in it. In what form is the energy stored by the cell?

5. State Ohm's law. Explain what is meant by electrical resistance, and describe some method of measuring the resistance of a coil of wire.

6. Explain the principle of the Wheatstone bridge method of comparing resistances. Describe a galvanometer suitable for use in the experiment.

7. Describe and explain how the resistance of a conductor can be measured by the post-office box.

8. Two wires in multiple arc (in parallel) are connected with a battery. Under what circumstances will a galvanometer connecting a point on one wire with a point on the other show no deflexion?

9. Define specific resistance, and describe a method of measuring it in the case of a wire. A wire, 1 metre long and 0·6 mm. diameter, is found to have a resistance of 1·16 ohm. Calculate the specific resistance of the material of the wire.

10. A battery of E.M.F. 2 volts, and resistance 0·5 ohm, is connected in series with a resistance of 2·5 ohms and an ammeter. The current recorded is 0·5 ampere. What is the resistance of the ammeter?

11. Explain what is meant by a shunt. A given milliammeter is graduated to read up to 0·15 ampere. Calculate the resistance of the shunt which will be required to enable the instrument to read up to 15 amperes.

12. Describe a Leclanché cell. Explain how cells are joined (*a*) in series, (*b*) in parallel. In what circumstances will each of these respectively produce the greater current?

13. Explain the terms electro-motive force and internal resistance, as applied to a voltaic cell. Given three cells each of E.M.F. 1 volt and internal resistance 0·4 ohm, show how to calculate the E.M.F. and internal resistance of the batteries which may be constructed, using all the cells.

14. If the potential difference between the poles of a voltaic cell, when no current is flowing, is 1·4 volt, and is reduced to 1·1 volt when the poles are joined by a wire of 5 ohms resistance, find the internal resistance of the cell.

[Considering the wire a PD of 1·1 volt produces a current of $\frac{1 \cdot 1}{5} = 0 \cdot 22$ ampere. This is current in the circuit. ∴ E.M.F. of 1·4 volt produces a current of 0·22 ampere, etc.]

15. Describe and explain some accurate method of comparing the electro-motive forces of two cells.

16. Define what is meant by a watt, a joule, and a volt; and state the connection between them

17. Define the terms resistance, specific resistance. The length of the filament in a 200-volt 20-watt tungsten filament lamp is 60 cms. The specific resistance of tungsten is 5×10^{-5} ohm per cm. cube. What is the diameter of the filament?

18. Electrical power is supplied to a factory from a power station by means of two cables, each 3 miles long. The potential difference between the ends of the cables at the power-house is maintained at 220 volts, and the potential difference between them at the factory must not fall below 200 volts. What is the greatest permissible resistance per mile of the cable if the maximum current required is 40 amperes?

CHAPTER XIV

THERMAL EFFECT OF A CURRENT—THERMO-ELECTRICITY

359. Production of Heat by a Current. We have seen (§ 342) that if a battery of E.M.F. E maintains a current C in a circuit for t seconds, the work done by the battery on the circuit is E . C . t ergs if E and C are in absolute units, or E . C . $t \times 10^7$ ergs if they are measured in volts and amperes This energy can be used for decomposing chemical compounds, as in the electrolytic cell, or for running an electromotor, which will transform it into mechanical energy. If, however, the poles of the cell are simply joined by a metallic wire, the energy is transformed into heat.

The heating effect of a current can readily be shown by joining the poles of a battery by a thin conducting wire. The wire rapidly becomes hot to the touch. If the wire is very thin, as in the case of the filament of an electric lamp, the heat generated is sufficient to raise the wire to a white heat.

If a current C (ampere) flows in wire of resistance R (ohms) the difference of potential between the ends of the wire is C . R volts. Now the energy w spent in the wire in a time t seconds is, as we have seen, given by

$$\begin{aligned} w &= E \,.\, C \,.\, t \text{ joules} \\ &= (CR) \,.\, C \,.\, t \text{ joules} \\ &= C^2R \,.\, t \text{ joules} \\ &= C^2Rt \times 10^7 \text{ ergs} \end{aligned}$$

As this is all transformed into heat, the heat H produced in the wire in the time t is given by

$$JH = C^2Rt \times 10^7$$

where J is the mechanical equivalent of heat (§ 164).

The heat produced is thus—

(*a*) directly proportional to the square of the current;

(*b*) directly proportional to the resistance of the conductor;

(*c*) directly proportional to the time for which the current flows.

These results can be verified experimentally with the apparatus shown in Fig. 280. A small copper calorimeter containing a suitable amount of water is fitted with a lid through which pass two stout copper wires which are connected inside the calorimeter by a coil of fine insulated

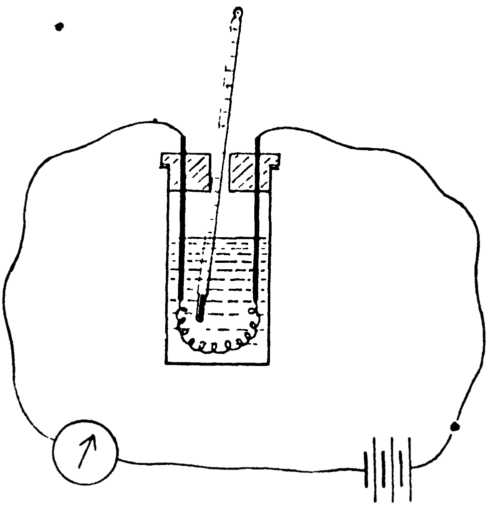


FIG. 280.—Determination of the Heat produced by a Current.

wire immersed in the water. The resistance of the coil is measured before the experiment. A sensitive thermometer passing through a hole in the lid measures the temperature of the water.

The coil is connected in series with a battery of two or three cells, and an ammeter to measure the current. The current can be adjusted by means of a sliding resistance.

The circuit is made and the current allowed to flow for a given time, and the heat developed in the calorimeter is calculated from the rise in temperature—the usual calorimetric precautions being taken to prevent loss of heat.

If the current is doubled, the heat produced in a given time will be increased fourfold. If the current is kept constant, the heat produced will be found to be directly proportional to the time for which it is allowed to pass. Finally, if a second heating coil of different resistance is substituted for the first, it can be shown that the heat produced is directly proportional to the resistance of the coil, if the current remains the same.

360. Electrical Determination of J.—The apparatus just described can be used to determine the mechanical equivalent of heat. A constant current, which is measured by an ammeter, is passed through the heating coil for a given time t, and the heat produced calculated from the rise in temperature of the calorimeter and its contents. As it takes some little time to produce a measurable rise in temperature, corrections should be applied for the loss of heat from the calorimeter by radiation, etc. If the resistance of the heating coil is measured, the value of J can be calculated from the equation

$$JH = C^2Rt \times 10^7$$

H being measured in calories, C in amperes, and R in ohms.

It is more accurate to measure directly the difference of potential between the ends of the heating coil by connecting the ends of the coil to the terminals of a voltmeter, the voltmeter being read from time to time while the current is flowing. If E is this potential difference in volts, then, by our original equation

$$JH = ECt \times 10^7$$

The value of J deduced in this way agrees with that obtained by mechanical methods—a further confirmation of the principle of the conservation of energy.

361. Production of a Current by Heat.—If a bar of copper and a bar of iron are soldered together at both ends (Fig. 281), and a compass needle is pivoted on a support between them, it is found that if one of the junctions is heated a current flows round the circuit, and the needle is deflected. The direction of the deflexion shows that the current flows from the copper to the iron across the hot junction, and from the iron to the copper across the cold junction. This experiment is due to Seebeck, and the phenomenon is known as the **Seebeck effect.**

The combination of the two dissimilar metals is known

as a **thermo-junction,** or **thermo-couple,** and the current produced as a **thermo-electric current.**

Any pair of dissimilar metals can form a thermo-junction. The greatest effect is produced by a couple of antimony and bismuth. It is not necessary that the metals used to form the thermo-junction should themselves make a complete

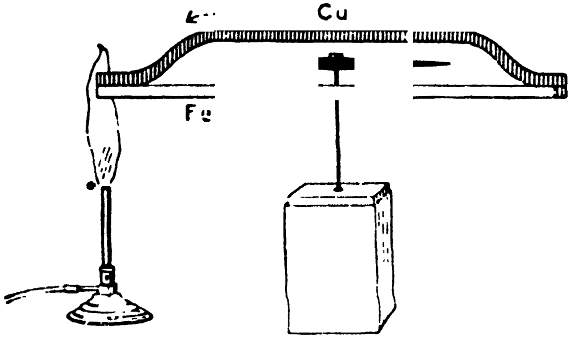


FIG. 281.—Seebeck's Experiment—Production of a Current by Heat.

circuit. If a bar of bismuth and a bar of antimony are soldered together at one end, and their free ends connected by copper wire to a sensitive galvanometer, a current will flow round the circuit if the bismuth-antimony junction is heated.

The effect on the galvanometer is increased if a number of these couples are joined in series as shown in Fig. 282.

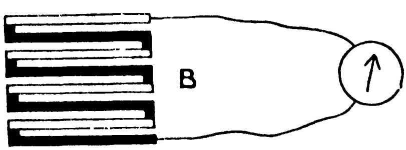


FIG. 282.—Principle of the Thermopile.

This arrangement is known as a **thermopile,** and is one of our most delicate means of detecting small quantities of radiant heat. If one face of the thermopile, say B, is kept at a constant temperature while the other is exposed to a source of radiation, the exposed face becomes slightly warmer than the other, and a current flows round the circuit and may be detected by the galvanometer. The current

increases with the difference in temperature between the two faces.

The thermo-electric currents are usually very small. If one junction of a bismuth-antimony couple is at 100° C. and the other at 0° C., the E.M.F. produced in the circuit is only 0·008 volt, and the current produced in a galvanometer of, say, 8 ohms resistance would only be 0·001 ampere, or one thousandth of an ampere. A good galvanometer is, however, capable of detecting currents as small as one thousand-millionth of an ampere, and would thus detect a difference of temperature between the ends of the couple of one ten-thousandth of a degree. It is the sensitiveness of the galvanometer that makes the thermopile such a delicate means of detecting small quantities of radiant heat.

A thermo-couple is also frequently employed for measuring high temperatures, such as that of a furnace. In this case a single couple, usually of platinum and of a platinum rhodium alloy, or other metals capable of withstanding high temperatures, is used. The couple is connected in series with a suitable galvanometer. The deflexion of the galvanometer increases as the temperature of the hot junction is increased. The instrument is calibrated by comparison with a standard air thermometer.

362. Effect of Temperature on Resistance.—The resistance of a metallic conductor increases with the temperature; the higher the temperature, the greater the resistance. The relation between temperature and resistance for a pure metal can be expressed in the form

$$R_t = R_0(1 + \alpha t + \beta t^2)$$

where R_t is the resistance at t° C., and R_0 that at 0° C.

As the measurement of the resistance of a wire can be carried out with great accuracy, this result affords us a very accurate method of measuring temperatures. The metal employed is generally platinum, as it can withstand a very high temperature, and is not readily oxidised or otherwise affected. A *platinum thermometer* consists simply of a suitable length of platinum wire wound on an insulating mica frame, the wire and frame being enclosed in a porcelain tube to protect them from damage. The terminals of the wire are connected by long flexible leads to the measuring apparatus.

To measure the temperature of a bath or furnace, the thermometer is placed in it in the usual way, and the resistance R_t of the coil is measured by the P.O. box. If R_0 its resistance at 0° C. is known, and the constants α and β of the equation, the temperature t can be calculated from the equation.

Since the equation contains two unknown constants, three fixed points are required to calibrate the thermometer. These are usually the freezing-point and boiling-point of water, as in the ordinary mercury thermometer, and in addition the boiling-point of sulphur (445° C.). The platinum thermometer has a very long range, from the lowest temperatures obtainable to the melting-point of platinum (about 1700° C.), and with suitable apparatus for measuring resistance is extremely sensitive.

The resistance of a conductor decreases as the temperature falls. When the experimentally determined values are substituted in the equation above, it is found that the resistance of the platinum wire should be zero at a temperature just above −273° C., that is, just above the absolute zero. A similar result is obtained for all pure metals. This deduction has been actually verified by immersing a lead wire in rapidly boiling liquid helium, which has a temperature of about 2° absolute—that is, −271° C. It is found that at this temperature the resistance of the lead wire is too small to be detected even by the most sensitive apparatus.

The variation of resistance with temperature is far less rapid in alloys than in pure metals. In certain special alloys, such as platinoid, or manganin, it is so small as to be practically negligible. These alloys are employed in the construction of standard resistances, which are thus practically independent of changes in the temperature of the atmosphere.

Carbon, the only non-metal which is comparable to metals in conducting power, is exceptional, its resistance decreasing as the temperature rises. Thus the resistance of a carbon filament lamp is much less when the lamp is glowing than when it is cold; on the other hand, the resistance of a metallic filament lamp is greater when the filament is hot. The resistance of electrolytes also decreases as the temperature is raised.

CHAPTER XV

ELECTRO-MAGNETIC INDUCTION

363. Faraday's Experiments.—If a coil of wire A (Fig. 283) connected with a battery is placed parallel to a second coil B connected to a galvanometer, then, however large the current in A, so long as it is constant no effect will be produced on the galvanometer connected to the second coil B. The presence of a current in one conductor has no effect upon a neighbouring conducting circuit. Faraday, however, noticed that just at the instant when the current began to flow in the circuit A, the galvanometer in circuit with B gave a "kick,"

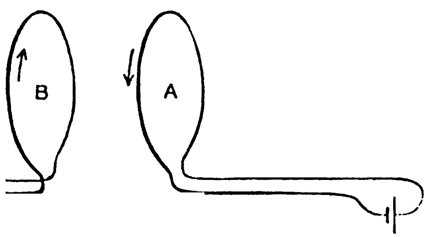


FIG. 283.—Experiment to illustrate the Induction of Currents.

showing that a transient current was produced in B. Similarly, on breaking the circuit A, a second momentary current was produced in B, but this time in the opposite direction. These currents are known as **induced currents**, and the phenomenon as **electro-magnetic induction.**

It is found that the current induced in B when the current first flows in A is in the opposite direction to the current in A. It is known as an "*inverse*" induced current. On the other hand, the current in B when the circuit A is broken is in the same direction as the current in A, and is called "*direct.*"

Similar effects can be produced by the relative motion of the two circuits. If the current in A is kept constant, and the distance between the circuits is altered, an induced

current will flow in B while the motion is taking place. Moving the circuits closer together has, as might be expected, the same effect as starting a current in A, while increasing the distance apart has the same effect as stopping the current—that is to say, the induced current in the first case is inverse, in the second direct.

Faraday found that the strength of the induced currents was very greatly increased if the two coils of wire were wound upon a ring of soft iron (Fig. 284). On passing a current through A and thus converting the iron into a magnet, a very strong inverse current was induced in the coil B, while on breaking the circuit a strong direct induced current was produced. Similar results were obtained if the coils were wound on a straight bar of iron.

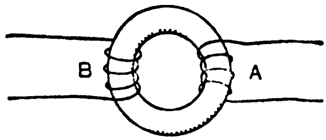


FIG. 284.—Induction of Currents—Action of a Soft Iron Ring.

364. Faraday's Experiments (continued).—Faraday then showed that induced currents could be produced in a conducting circuit, not only by other currents, but also by permanent magnets. If a permanent magnet NS (Fig. 285) is held near the coil B, as long as the magnet and coil are at rest, no current will flow in B. If, however, the magnet and

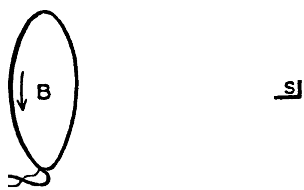


FIG. 285.—Induction of a Current by a Magnet.

the coil are moved either closer together or farther apart, currents will be induced in B, which will continue to flow so long as the motion is taking place.

The direction of the induced current in B can be deduced from the first experiments by regarding the magnetism of the magnet as being due to a current flowing round it (§ 325). Thus, if the north pole of the magnet is directed towards the coil, we may regard the north pole as being due to a current

flowing round the magnet in the appropriate direction (it will be clockwise as seen from the centre of the magnet). On bringing the *north* pole nearer the coil B, an inverse current will flow round the circuit B, which will therefore be *counter-clockwise* as seen from the magnet, as indicated in the figure. Conversely, on withdrawing the north pole the direct current induced in B will flow in a *clockwise* direction round B as seen from the magnet. These effects will obviously be reversed if the south pole of the magnet is used instead of the north pole. These results can easily be verified by experiment.

365. Laws of Induction.—Examining these phenomena it will be noticed that induced currents are produced when the magnetic field through the coil B is changing. When a current is started in A it produces lines of magnetic force, some of which pass through B and thus increase the field across it. When the current in A ceases to flow, these lines are withdrawn from B and the magnetic field through it is reduced. Similar changes are produced in the other experiments described. Any change which produces a change in the number of lines of magnetic force passing through a circuit will produce an induced current in it. For example, if a coil of wire standing with its plane in the magnetic meridian is turned into an east and west direction, the lines of the earth's horizontal magnetic field are caused to pass through the circuit, and a momentary induced current is produced. Faraday, by experimenting with coils of different shapes and sizes, proved that the quantity of electricity set in motion by the induced current was directly proportional to the total change in the number of lines of magnetic force through the circuit.

We have seen that when a current is made in the circuit A (Fig. 283) the induced current in B flows in the opposite direction to the inducing current. The lines of force due to the induced current are thus in the opposite direction to those of the inducing current—that is to say, they tend to keep the resultant magnetic field through B at its original value, or, in other words, to neutralise the change in the field produced by the starting of the current in A. On breaking the circuit A, the induced current is direct, and its lines of force are in the same direction as those of the current A which have now been destroyed. This result will be found to hold true in the other cases we have examined.

Faraday's results may be summed up in the following *laws of electro-magnetic induction* :

I. **Whenever the number of lines of magnetic force threading a conducting circuit is changing, an induced current flows round the circuit, which continues only while the change is actually taking place.**

II. **The direction of the induced current in the circuit is such as by its magnetic field to oppose the change which is taking place.**

III. **The total quantity of electricity set in motion is**

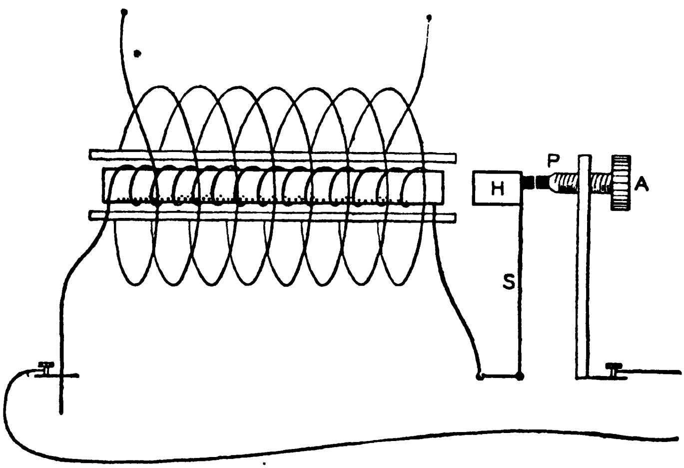


FIG. 286.—Principle of the Induction Coil.

directly proportional to the total change in the number of lines of magnetic force passing through the circuit.

366. **The Induction Coil.**—The principle of the induction of currents is used in the *induction* or *Ruhmkorff coil* to produce from a primary current of low voltage a secondary or induced current of very high voltage. It consists (Fig. 286) of a primary coil of one or two layers of thick copper wire wound in the form of a solenoid upon a central core of soft iron. This primary coil is completely enclosed in a tube of ebonite upon which are wound a very large number of turns of thin insulated copper wire, forming what is known as the secondary circuit. The greater the number of turns of wire in the

secondary coil the greater the difference of potential which will be produced between its ends.

If a current is started in the primary circuit, the core becomes a strong electro-magnet, and a strong magnetic field is produced through the secondary coil. Hence an induced current flows round the secondary circuit, which by the laws of induction is an inverse current. If the current in the primary circuit is broken, a direct induced current is produced in the secondary. For reasons which cannot be explained here, the induced current at "break" has a very much higher voltage than that at "make," and arrangements are generally made to eliminate the latter as far as possible.

As the induced current only flows so long as the primary current is changing, arrangements must be made to make and break the primary circuit continually—that is to say, we must send through the primary coil not a continuous but an intermittent current. This can be effected by various devices known as *interruptors* or "*breaks*." The smaller coils are fitted with an automatic device known as a hammer break. A soft iron hammer H is supported on a spring S close to one end of the core of the coil. This spring presses the hammer against a platinum contact P which can be adjusted by a screw. One of the wires from the primary is connected to the hammer, and a second wire leads from the contact P to the battery.

When the battery is switched on, the current flows from the screw through the platinum contacts and thence to the coil. As soon, however, as the current passes, the iron core becomes magnetised, and attracts the iron hammer, which moves towards it, thus separating the platinum contacts at P and breaking the circuit. But, the circuit being broken, the core ceases to be a magnet and the iron hammer is carried back against the screw, by the action of the spring, thus again completing the circuit. In this way the current is automatically made and broken a large number of times per minute.

The hammer break is not suitable for use with large currents such as are employed in modern coils, as the current arcs across the platinum contacts, which are rapidly ruined.

The potential difference of the induced currents in the secondary circuit is very high, comparable with or even greater than that produced by a Wimshurst machine, while the quantity of electricity conveyed by the currents is many

times greater. If the secondary terminals are approached, a torrent of sparks passes between them. The large coils used in modern radiography are capable of producing a rapid succession of sparks across an air gap of no less than 16 inches. The difference between the torrents of sparks from an induction coil and the feeble and intermittent discharge of a Wimshurst is very striking.

367. The Dynamo.—If a coil of wire ABCD (Fig. 287) is at right angles to a magnetic field H, and is then turned so that the plane of the coil becomes oblique to the lines of the field, the number of lines of force passing through the coil becomes progressively less, until, when the coil is parallel to the field, the number cutting the coil is zero. Hence, by the laws of induction a current flows round the coil in such a direction that the lines of force due to the current are in the same direction as those of the field—that is, the current must flow in the direction DCBA. If the coil is still rotated in the same direction, as shown in the lower half of the figure, the number of lines of force passing through it increases, and an induced current continues to flow round the circuit, its direction being now such as to reduce the magnetic field through the coil. It must be remembered, however, that the coil has rotated so that the side DC is now nearer the reader—that is to say, the current still flows round the coil in the direction DCBA.

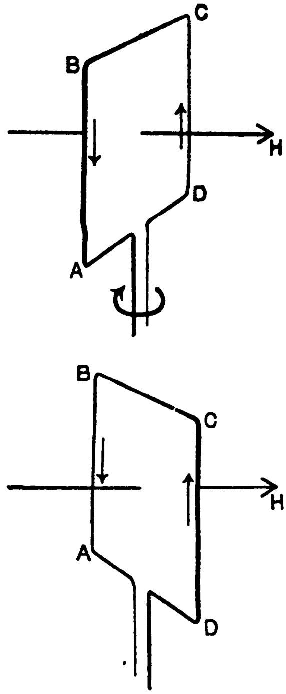


FIG. 287.—Production of a Current by Rotation of a Coil in a Magnetic Field.

After passing through the position where the plane of the coil is again at right angles to the field, the number of lines of force threading the circuit will decrease as the rotation continues. The current is therefore reversed and flows in the

direction ABCD, its field being in the same direction as H. Following the above line of argument, we can see that the induced current will continue to flow round the circuit in this direction until the coil has completed one revolution and is again in its original position.

Thus, if the coil is rotated continuously in the field at a uniform rate, induced currents will continue to flow in the coil, their direction round the coil being reversed every half-revolution. A current can be obtained in this way merely by rotating a coil in the earth's magnetic field. The coil then forms what is known as an **earth inductor.** Since the strength of the induced currents increases with the strength of the field it is obviously better, if the

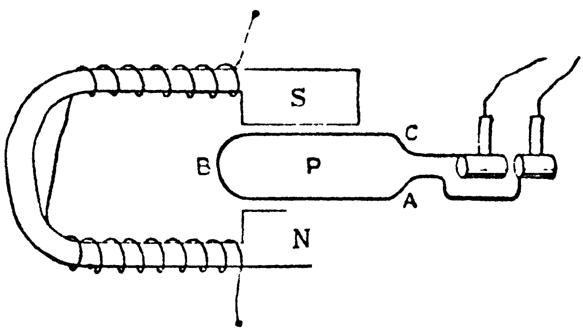


FIG. 288.—Principle of the Dynamo.

instrument is to serve as a source of current, to rotate the coil in the strong magnetic field between the poles of a horseshoe electro-magnet (Fig. 288); the instrument is then known as a **dynamo.**

The coil is made to rotate by mechanical means (*e.g.*, by a steam engine), and the two ends of the coil are fastened to two metal rings rotating on the same axis as the coil. Two conducting rods, or "brushes" as they are called, press lightly against the rotating rings, and thus enable contact to be made between the rotating coil and the ends of a fixed circuit.

The current in the circuit, as we have seen, will change its direction at each half-revolution of the coil. Such a current is known as an **alternating current,** and the machine described is a very simple type of an *alternating current dynamo.* The rotating coil is known as the **armature.**

For most commercial purposes an alternating current is as useful as a direct current—that is, as a current which always flows round the circuit in the same direction. For example, for electric lighting or heating, since the heat produced varies as the square of the current, it is independent of the direction in which the current flows, and hence an alternating current will light an electric lamp as efficiently as a direct current. Owing to various engineering advantages the current supplied commercially is usually alternating.

We can, however, very easily obtain a unidirectional or direct current from our dynamo, by reversing the connections between the circuit and the revolving armature at the moment when the direction of the current round the armature changes. This may be done very simply by connecting the two ends of the armature to the two halves of a split ring rotating on the armature shaft, the two halves of the ring being insulated from each other. Contact with the ring is made by brushes in the same way as before. A device of this kind is called a **commutator.**

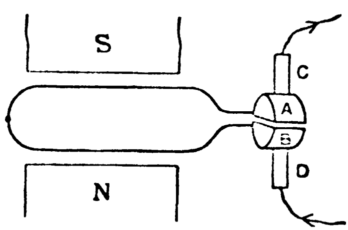


FIG. 289.—Principle of the Direct Current Dynamo.

Suppose that the coil is rotating so that the current is flowing from B to A (Fig. 289), the plane of the coil being parallel to the field. After a quarter of a revolution the current in the armature will reverse its direction. But in the same time A will have turned so as to make contact with the brush D, and B with the brush C, so that the current which now flows from A to B will continue to flow round the external circuit from C to D. Thus though the current in the armature is alternating, that in the external circuit is direct, or continuous as it is often called. This apparatus is a simple form of **direct current dynamo.**

The electro-magnet, or "field magnet" as it is called, can be excited by the current produced by the dynamo itself. If the "*field*" coils are connected in series with the rest of the circuit, the dynamo is said to be *series wound.* If, however, the field coils are connected directly with the brushes so that the magnet is in parallel with the main circuit, and only a

portion of the current flows through the field coils, the instrument is said to be *shunt wound.*

368. Electromotors.—The dynamo is a reversible instrument. If we rotate the armature by mechanical means an electric current is generated, as we have seen; and mechanical energy is thus converted into electrical energy. If, on the other hand, we pass a current through the armature from some external source the armature is made to rotate (by the magnetic forces set up between the magnetic poles and the current in the armature) and the electrical energy is converted into mechanical energy. The machine thus forms an **electromotor.**

CHAPTER XVI

DISCHARGE OF ELECTRICITY THROUGH GASES—X-RAYS

369. The Electric Spark.—Air at ordinary atmospheric pressures is a good insulator of electricity. By very delicate methods it can be shown that the insulation is not quite perfect; but the leakage from a conductor surrounded by air is extremely small. On the other hand, the existence of an electric field puts the molecules of air under strain, and if the field is too great the insulation breaks down and a spark passes. The maximum field that air can sustain at its ordinary pressure and temperature is about 30,000 volts per centimetre. If the field rises beyond this value a spark discharge takes place.

The potential difference required to produce a spark decreases as the pressure of the air becomes less. The experiment can be carried out in a long glass tube sealed at both ends and connected by a side tube to an exhaust pump. Electrodes, usually in the form of small aluminium disks, are sealed into the ends of the tube by means of platinum wires. These wires are connected to the secondary terminals of a small induction coil. As the tube is gradually exhausted it will be found that the discharge takes place more and more readily. The spark at the same time becomes wider, more diffuse, and more continuous, until at a pressure of a few millimetres of mercury the whole tube becomes filled with a continuous reddish glow. At this stage the difference of potential necessary to maintain the discharge is reduced to a few hundred volts.

370. The Discharge Tube at Low Pressures.—If the tube is still further exhausted by means of a vacuum pump (§ 91) to a pressure of about $\frac{1}{10}$th mm. of mercury, the character of the discharge suddenly alters, the continuous glow being replaced by a series of bright and dark bands or striæ. The appearance of the discharge tube at this stage is shown in Fig. 290.

The surface of the cathode itself is covered with a bluish velvety glow, known as the cathode glow. Beyond this the discharge for some little distance appears dark and non-luminous. This dark portion is known as the Crookes dark space. Still farther along the tube this dark space merges into another luminous patch known as the negative glow, beyond which we have a second region of darkness known as the Faraday dark space. The whole of the tube between the Faraday dark space and the anode is occupied with a set of bright button-shaped patches of light, their convexities facing the cathode. This portion of the discharge forms the positive column. At a pressure of $\frac{1}{10}$th mm. of mercury the positive column fills the greater part of the tube, the other phenomena being confined to within a centimetre or so of the cathode. As, however, the pressure is still further

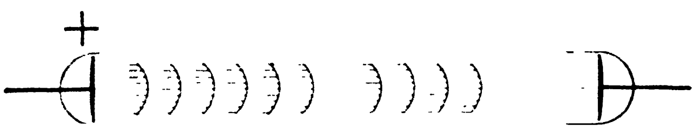


FIG. 290.—Electric Discharge in a Gas at Low Pressure.

reduced, the Crookes dark space begins to grow at the expense of the other appearances, until finally, at very small pressures indeed, it occupies the whole of the tube, except for a glow on the surface of the cathode and a little blob of light on the anode. At the same time the potential difference required to maintain a discharge through the tube rapidly increases, running up into hundreds of thousands of volts. It is indeed possible to exhaust a tube so highly that the highest potential difference producible is insufficient to cause a discharge to pass.

371. Cathode Rays.—If the tube is exhausted to the stage when the Crookes dark space very nearly fills the tube, a pencil of pale blue light will be seen, proceeding normally from the cathode and crossing the dark space. It is known as the **cathode rays.** If the tube is arranged so that the cathode rays fall upon the glass walls of the tube, the portion of the glass which receives the rays glows with a greenish yellow fluorescent light.

The cathode rays consist of negatively charged particles shot off from the negatively charged surface of the cathode with very great velocity. These cathode particles, or electrons as they are now called, are very much lighter than the lightest known atom. The charge they carry is, however, exactly the same as that carried by any negative monovalent ion in electrolysis. The evidence for these statements can be summarised as follows:

(*a*) SHADOWS CAST BY THE RAYS.—If a solid obstacle such as a mica cross (Fig. 291) is placed in the discharge tube in the path of the cathode rays, a sharp shadow of the cross is thrown by the rays on the farther wall of the tube.

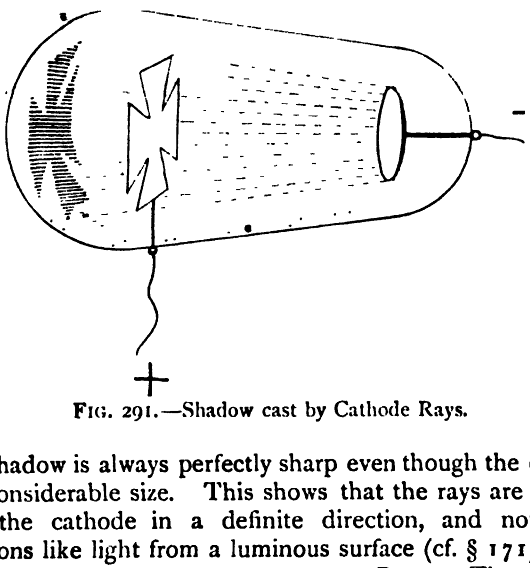


FIG. 291.—Shadow cast by Cathode Rays.

This shadow is always perfectly sharp even though the cathode is of considerable size. This shows that the rays are emitted from the cathode in a definite direction, and not in all directions like light from a luminous surface (cf. § 171).

(*b*) MAGNETIC DEFLEXION OF THE RAYS.—The cathode rays are deflected by a magnet. This can easily be shown with a discharge tube such as that in Fig. 292. The cathode C is a flat aluminium disk, while the anode A is a brass plate perforated by a small hole in the centre. A narrow pencil of cathode rays passes through the hole, the rest being stopped by the plate. This pencil forms a sharp bright patch of fluorescent light on the farther end of the tube. If the pole N of a magnet is brought near the tube, say at X, the spot of fluorescence moves, showing that the path of the rays has been

deflected by the magnet. The deflexion is the same as that which would be produced under the same circumstances in a flexible conductor carrying a current from O to C, and coinciding with the original path of the rays. The rays, therefore, behave towards the magnetic field just like a current.

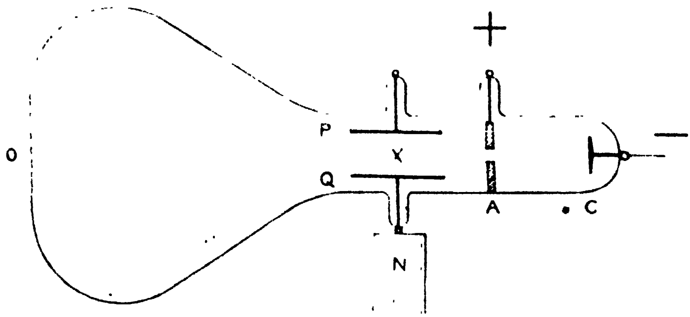


FIG. 292.—Magnetic and Electrostatic Deflexion of Cathode Rays.

(*c*) ELECTROSTATIC DEFLEXION OF THE RAYS.—Again, if the narrow pencil of cathode rays is passed between two parallel plates P and Q charged to a difference of potential of a few hundred volts, it is again deflected, the particles being attracted towards the positive plate. The particles in the

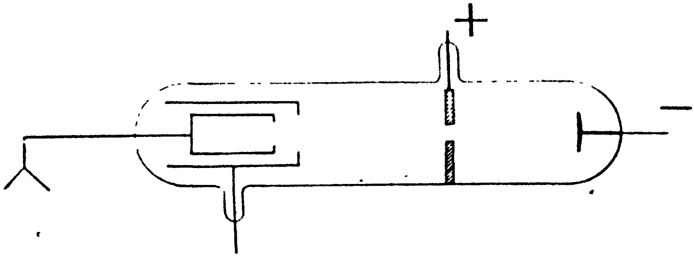


FIG. 293.—Apparatus to show the Charge carried by Cathode Rays.

rays, being attracted by a positive plate, must themselves be negatively charged.

(*d*) NEGATIVE CHARGE ON THE RAYS.—The negative charge carried by the rays can be demonstrated directly by allowing the pencil of rays to fall into a brass cylinder connected to an electroscope (Fig. 293). As there is a strong

and variable electrostatic field inside the discharge tube, it is necessary to protect the cylinder from electrostatic disturbances by surrounding it by a somewhat larger metal cylinder connected to earth. This device is known as a Faraday cylinder, as Faraday was the first to show that such an arrangement provided a perfect screen against external electrical forces (§ 285). As soon as the cathode rays enter the inner cylinder, the leaves of the electroscope diverge, the sign of the electrification being negative.

372. Electrons. The particles which form the cathode stream are known as electrons. They may perhaps best be described as atoms of electricity. No charge smaller than that carried by an electron has been isolated, and there is evidence to prove that every charge consists of an integral multiple of this charge, just as every mass of substance is made up of a whole number of atoms. It has been proved that the charge on a monovalent ion in solution is exactly equal to the charge upon an electron.

The velocity of the particles in a cathode beam and their electro-chemical equivalent (that is, the ratio of the mass of a single electron to the charge upon it) can be determined by comparing the deflexions produced in the beam by a magnetic and by an electric field. The experiment which was devised and carried out by Professor Sir J. J. Thomson can be performed with apparatus similar to that of Fig. 292, and already described. The velocity of the rays increases with the potential difference across the tube. It is generally of the order of one-tenth of the velocity of light. The ratio of the mass of an electron to its charge, however, is invariably the same. It is quite independent, not only of the potential of the discharge, but also of the nature of the metal forming the cathode and of the gas remaining in the tube. It is thus a universal constant. According to the best determination its value is about $5{\cdot}6 \times 10^{-9}$ grams per coulomb. Now the ratio of the mass of a hydrogen ion to the charge upon it (the electro-chemical equivalent of hydrogen) is approximately 10^{-5} grams per coulomb. Since the charge on each of these particles is the same, the mass of an electron must be, therefore, about $\frac{1}{1770}$ that of a hydrogen atom. It is, therefore, much lighter than any material atom.

The actual values of the charge on an electron and its

mass have now been determined. The electronic charge, or atom of electricity, is $1{\cdot}57 \times 10^{-19}$ coulombs. Substituting this value in the value for the ratio of the mass to the charge we see that the mass of an electron is $8{\cdot}8 \times 10^{-28}$ grams.

Since these electrons can be given off from any kind of substance they must be present in all kinds of matter. On the modern theory of matter every atom consists of a number of electrons (equal approximately to half the atomic weight) revolving around a central positive charge, like planets round the sun. As the radius of an electron is only about $\frac{1}{100000}$th of that of the atom itself, it is obvious that an atom, like the solar system, consists principally of spaces. A single electron, therefore, can make its way through solid matter with no more difficulty than a planet crossing the solar system.

373. Electron Theory of Conduction.—It is believed that conduction through metals is carried on by the motion of electrons such as we have described. In non-conductors the electrons in the atom are too rigidly attached to it to be set in motion by the electrical forces usually employed. In the case of conductors, however, it is supposed that a certain number of the electrons are so loosely attached to the atoms that a considerable number of them are always in a free state, and are therefore moving about in the metal, like the molecules in a gas. If an electric field is now applied across the conductor, the electrons move under the field from the negative to the positive end of the conductor, carrying their charges with them. This motion of the electrons through the conductor constitutes the electric current.

374. X-Rays.—It was observed by Röntgen that certain radiations were given off from the walls of the discharge tube at the points where the cathode rays impinged. To these rays, which were able not only to penetrate the glass walls of the tube but also many other substances which are opaque to ordinary light, he gave the name **X-rays**, as their nature was unknown. They are often called **Röntgen rays**, after their discoverer.

X-rays are now known to be vibrations in the ether resembling those of light, but very much more rapid, and therefore of much shorter wave length. The wave length of the X-rays is indeed only about $\frac{1}{5000}$th of that of the light waves making up the visible spectrum. Like the ultra-violet rays, they are non-luminous—that is to say, they do not pro-

duce the sensation of vision when allowed to fall on the retina. We can only observe them by the effects which they produce.

If a sheet of cardboard is covered with crystals of barium platino-cyanide, it becomes luminous when struck by the rays. Such an arrangement is known as a fluorescent screen, and is very useful for observations on the rays. If an object which is opaque to the rays is placed between the source of the rays and the screen, it will cast a dark shadow on the screen, since X-rays, like other forms of light, travel in straight lines.

Again, the X-rays act upon the emulsion of a photographic plate in the same way as ordinary light. A photographic plate placed in the path of the rays will, on being developed in the usual way, be found to have become blackened. If, however, an opaque object is placed in the path of the rays in front of the plate, there will be no action on that part of the film within the shadow of the object. Thus, on developing the plate, a photographic image of the shadow cast by the object will be obtained.

This process is known as radiography, and the resulting picture as a radiogram, or skiagram. It is of course a "negative"—that is to say, the parts in the shadow will be clear, while those not in the shadow will appear dark. A "positive" can be obtained from this negative by printing on photographic paper in the usual way.

375. Properties of X-Rays.—X-rays, like light, travel in straight lines, from the point struck by the cathode rays. Their intensity, therefore, like that of light, falls off inversely as the square of the distance from the point of origin. Owing to their very small wave length they can neither be reflected or refracted.

No substance is absolutely opaque to the rays, but some substances are far more so than others. The denser the substance, the more opaque it is to the rays. The opacity to the rays depends also on the nature of the elements making up the substance. Elements of high atomic weight are much more opaque to the rays than elements of low atomic weight. Thus iron, copper, nickel, and lead stop most of the rays falling upon them, and thus cast very dense shadows; aluminium, bone, and glass, which absorb a smaller proportion of the rays, throw shadows of less density; while paper, cotton wool, wax,

wood, or flesh, being substances of low density and consisting entirely of elements of low atomic weight, are very transparent to the rays, and cast only faint shadows. Thus in the case of a human limb, the shadow cast by the bone stands out very distinctly from the faint shadow of the flesh surrounding it, while a piece of shrapnel embedded in the flesh will cast a

FIG. 294.—Radiogram showing a Dislocation of Elbow-Joint.

still denser shadow. Thus, if the limb is placed between the origin of the rays and a fluorescent screen, the shadow of the bones are distinctly visible on the screen, being much darker than the surrounding flesh, while the presence of a piece of metal is at once apparent. If a photographic plate is placed in the position of the fluorescent screen a permanent record of the appearances is produced. Fig. 294 is a reproduction of such a radiogram. It is obvious that this property of the rays renders them of enormous service in surgery.

376. Production of X-Rays.—It is obvious that if sharp shadows are to be obtained the X-rays must come from as small a point as possible (§ 171). If the discharge in the tube is a strong one, great heat is generated at the point struck by the cathode beam. It must be remembered that the cathode rays are travelling with enormous velocity, approaching 10^{10} cms. per second. As the kinetic energy of a particle is proportional to the square of its velocity it is obvious that a very large amount of energy will be conveyed to the point struck by the cathode stream. This energy is mainly transformed into heat. The modern X-ray tube is designed (*a*) to obtain as sharp a focus of the cathode rays as possible, and

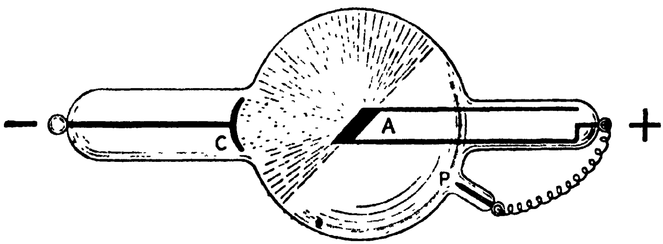


FIG. 295.—X-Ray Tube.

(*b*) to get rid of the large quantities of heat generated by the cathode rays at the focus.

Fig. 295 is a diagram of a modern X-ray tube. The cathode C is made with a concave spherical surface. Since the cathode rays are emitted at right angles to the surface of the cathode, all the rays will meet approximately at the centre of this sphere. At this point is placed the *target*, or *anticathode* A, which consists of a block of polished tungsten (a very hard, infusible metal) let into the surface of a thick copper disk. This disk forms the end of a copper tube, which being a good conductor of heat rapidly conveys the heat away from the focus of the rays, and having a large surface radiates it out into the air.

The end of the anticathode is bevelled at an angle of 45° to the axis of the tube. The X-rays radiate out fairly uniformly over the hemisphere in front of the anticathode. The anticathode is connected by a wire outside the tube to the anode P, a small aluminium rod placed near the anticathode. The tube is exhausted to a high vacuum.

The current is passed through the tube from a large induction coil (§ 366). With a high-power apparatus it is possible to pass a current of as much as $\frac{1}{10}$th of an ampere through such a tube, at a potential difference of half a million volts. With discharges of this intensity it is possible to take a radiogram through a man's body in $\frac{1}{100}$th of a second.

377. Conduction through Gases.—The X-rays have the property of increasing the conductivity of a gas through which they are passing. Insulated conductors rapidly lose their charges if an X-ray tube is being worked in their neighbourhood. It is found that the X-rays cause some of the molecules of the gas to give out one of the electrons which it contains, thus leaving the molecule itself positively charged. The electron is then attracted by one of the neutral molecules around it, which thus receives a negative charge. In this way a number of positive and negative molecules are formed in the gas, which can convey a current through the gas in the same way as the charged ions convey the current through an electrolyte. These charged molecules are known as *gaseous ions*. Since the charge on an electron is the same as that carried by a monovalent ion in electrolysis, the gaseous ions and the electrolytic ions carry equal charges.

The number of ions present in the gas, even when the X-rays are very intense, is very small compared with the number of ions in an electrolyte, and the current which can be conveyed through the gas is under ordinary circumstances exceedingly small (about 10^{-10} amperes). A study of these currents has, however, led to results of very considerable theoretical importance.

EXAMINATION QUESTIONS.—XIX

1. How would you show that the heat developed in a wire in which a current is flowing varies as the square of the current?

2. A cell capable of maintaining a constant potential difference of 2 volts between its terminals is used to send a current through two resistance coils each of 2 ohms resistance. Compare the rates of production of heat in the coils (*a*) when they are connected in series, (*b*) when they are connected in parallel.

3. State the law concerning the generation of heat in an electric circuit. A wire resistance has its terminals maintained at a potential difference of 100 volts. If the current through the wire is 5 amperes, how many calories of heat are developed per hour?

4. An electric kettle working off the 220-volt circuit will raise a litre of water from 12° C. to boiling-point in ten minutes. Calculate the current through the kettle. (The whole of the heat produced may be assumed to be given to the water.)

5. Discuss the effect of temperature upon the resistance of a metal. How may the effect be used to measure high temperatures?

6. Describe some delicate instrument for detecting heat radiation, and explain the principles involved.

7. What is an induced current? Describe some of the ways in which a current can be induced in a circuit.

8. How would you illustrate the phenomenon of the induction of currents?

9. A large coil of wire lying on a table has its ends joined to the terminals of a galvanometer. Explain what happens (*a*) when the coil is turned over, (*b*) when it is turned over a second time.

10. Describe the construction and explain the action of an induction coil. Why is it important that the current in the primary should be interrupted rapidly? How is this effected in practice?

11. Describe a method by which alternating current may be generated.

12. Describe some machine by which direct current can be

produced by mechanical means. Explain the principles on which it acts.

13. Discuss the evidence for the statement that the cathode rays consist of negatively charged particles.

14. What are X-rays, and how are they produced? Give a brief account of the properties of the rays.

15. What do you understand by the term ion? Describe briefly the part the ions play in the transmission of electricity through gases and liquids.